Robust Shelter Location/Allocation in Humanitarian Logistics Networks

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Abstract

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Every year, various natural disasters such as earthquakes and hurricanes strike our planet that account for over hundred-thousand casualties and hundred-millions affected across the globe. While destroying buildings and bridges, such natural phenomena cause roads to be blocked and areas to be unreachable, electricity to be unavailable, to name a few consequences among others. Besides that, the affected population needs to be transferred to medical centers and/or sheltered, provided with food, water, electricity, and other primary needs. Such tremendous demand for housing and emergency supplies is usually more than available resources. Hence, effective pre- and post-disaster logistics activities are essential in order to reduce the number of casualties. Motivated by the importance of preparedness planning in improving emergency logistics, this thesis is focused on the problem of locating temporary shelters and allocation of affected population to those shelters in the context of earthquakes. The aforementioned problem is formulated as two-stage stochastic and robust optimization models so as to incorporate the uncertain frequency, epicenter and magnitude of earthquakes that directly impacts the housing demand as well as availability of shelters and the transportation network. Along with introducing various corrective actions to hedge the preparedness plan against different earthquake scenarios, we also consider Conditional-value-at-Risk as the risk measure in the two-stage stochastic formulation. The idea is to protect the plan against a certain percentage of worst-case scenarios. More specifically, the robust model would make sure that the number of affected population that cannot be transferred to shelters (and consequently, the number of casualties) is minimized under a given confidence level. A case study inspired by a real earthquake is also designed that provides the opportunity to validate shelter location/allocation models proposed in this thesis. Finally, we run a set of computational experiments in order to compare the performance of deterministic, stochastic, and robust optimization models.

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Chapter 1: Introduction

A sudden, dreadful, and unexpected event that causes people, environment, and material losses is called a disaster. A disaster can also be the result of a vast ecological breakdown in the relations between man and his environment (Cahill et al. (2003)). Disasters can be manmade (wars or terrorist activities) or natural (earthquakes, floods, tornadoes). In this thesis, we confine our attention to natural disasters. Due to the geographical features of distinct areas on the globe, each natural disaster can happen in a specific region. For instance, the most common natural disasters in the United States are floods, tornadoes, and blizzards. On the other hand, earthquake is the one with which human are struggling for survival in the Far East. Every year, more than 500 disasters are estimated to strike our planet, killing around 75,000 people and impacting more than 200 million others (Caunhye et al. (2012)). Along with destroying buildings and bridges, earthquakes and floods cause roads to be blocked and areas to be unreachable, electricity to be unavailable, etc. Besides that, injured people should be transferred to hospitals or medical centers. In addition, a huge part of evacuees need to be sheltered and provided with food, water, electricity, and other primary needs.

Caunhye et al. (2012) stated that Fritz Institute performed logistics planning manually during the 2004 Indian Ocean tsunami without the presence of logistics experts. In the 7 Richter Haiti earthquake, according to OCHA -The United Nations Office of The Coordination for Humanitarian Affairs: “Logistics and the lack of transport remain the key constraints to the delivery of aid”. Also, many journalists’ reports demonstrated that relief efforts were weak and stopped due to slow operations followed by undelivered aid (Caunhye et al. (2012)).

The word “logistics”, originally, comes from military field, meaning the science of supplying, movement, and maintenance of military forces. All the tasks that should be performed for a planned or organized event or activity to fulfil a purpose is called Logistics (Pan American Health Organization (2001)). Humanitarian logistics is a branch of logistics with a particular focus on organizing the warehousing and delivery of supplies during natural disasters or complex manmade emergencies to affected people in the area. Management of emergency logistics comprises four phases including mitigation, preparedness, response, and recovery planning.

In this thesis, we confine our attention to emergency (relief) logistics with a particular focus on preparedness decisions in the case of earthquakes. Since, one of the main activities in preparedness phase incorporates temporary housing of evacuees; we propose mathematical planning models for location/allocation of shelters. More specifically, these models seek the optimal location of temporary shelters along with the allocation of demand zones (i.e., affected population after an earthquake strikes) to those shelters. The objective is to minimize the initial investment for opening shelters in addition to transportation cost such that the maximum number of affected population is transported to shelters within 72 hours after earthquake.

Similar to other natural disasters, earthquakes are featured with uncertain frequency of occurrence, time, location, and magnitude. Such uncertainties would impact the number/location of affected population, the availability of shelters and transportation network, and the evacuation/transportation time from demand zones to temporary shelter. This calls for robust decision models that are protected against the aforementioned uncertainties. Hence, in this thesis, two-stage stochastic programming and robust optimization approaches are adopted to formulate the shelter location/allocation problem while considering uncertain nature of earthquakes. We propose various corrective (recourse) actions in the two-stage stochastic models as responses to earthquake scenarios. The objective of such stochastic models is to minimize the expected cost over all plausible scenarios. With the goal of incorporating risk measures in this problem, we also introduce Conditional-Value-at-Risk (CVaR) in the objective function of two-stage stochastic models, leading to robust optimization formulations. The goal is to minimize the number (and cost) of population that cannot be transported to shelters within 72 hours after earthquake under a given percentage of worst-case scenarios. This would lead to a lower number of casualties under extreme earthquake scenarios.

Further, an earthquake evacuation case study inspired from real data is carefully designed for validating proposed stochastic and robust optimization models. Various earthquake scenarios are also generated that represent realistic post-disaster circumstances. Finally, "the expected value of perfect information" and "value of stochastic solution" are the two criteria selected in order to evaluate the performance of stochastic models with their deterministic counterparts. We also compare the performance of two-stage stochastic models with the robust optimization one where Conditional Value at Risk (CVaR) is considered as the risk measure.

The main contributions of the thesis, thus, revolve around *i*) formulating novel stochastic and robust shelter location/allocation models in the context of earthquakes while taking into consideration the uncertain behaviour of such natural phenomena; and *ii*) generating a realistic case study and scenario set that can be used for validating other pre-disaster emergency planning models along with the proposed models in this thesis. Such data set is also useful for developing a simulation platform that mimics the evacuation process in an earthquake by considering various configurations for shelters and other emergency centers.

The rest of thesis is organized as follow. The detailed description of emergency logistics along with the relevant literature is presented in Chapter 2. Chapter 3 provides a brief description of two-stage stochastic programming and robust optimization approaches that constitute the main methodologies in this thesis. In Chapter 4, we present the problem description and formulation in both deterministic and stochastic contexts. Chapter 5 is dedicated to the description of case study and computational results. Finally, Chapter 6 concludes the thesis while providing future research avenues related to this study.

Chapter 2: Literature review

In this chapter, we first describe the main features of humanitarian logistic networks with a particular focus on emergency (relief) supply chains. Next, we mainly focus on the review of the existing literature on facility location/allocation problem in emergency logistic networks which can be classified as disaster preparedness planning in the aforementioned supply chains. We conclude this chapter by summarizing the existing gaps in the literature along with main contributions of this thesis.

2.1. Humanitarian Logistic networks

Kovács and Spens (2007) investigated contrasts between business and humanitarian supply chains (SCs). They showed that unlike business SCs, neither actors can be predicted in advance, nor demand is foreseeable in humanitarian logistic networks (HLNs). Later on, McLachlin et al. (2009) analyzed logistic networks in terms of environment and motivation. According to the authors, environment can be either interrupted or uninterrupted, while actors' motivation could be "for-profit" or "not-for-profit". They concluded that the case of uninterrupted environment and for-profit motivation of actors happen in the business context. On the other hand, disaster relief is the outcome of not-for-profit motive and interrupted environment. Kleindorfer and Saad (2005) stated that in humanitarian logistics "time is life" while in business logistics "time is money". Furthermore, the birthplace of money in the circle of business is customers paying currency whilst donors are the one with whom we are dealing in humanitarian logistics.

Some of the key challenges to HLN planning as compared to the business SCs are highlighted in Caunhye et al. (2012) as follows:

1. Additional uncertainties such as unusable routes, safety issues, changing facility capacities, demand uncertainties;
2. Complex communication and coordination, i.e., damage to communication lines, involvement of many third parties, government, and civilians, and inaccessibility to accurate real-time demand information;
3. Harder-to-achieve efficient and timely delivery; and

4. Limited resources (e.g., supply, people, transportation capacity, fuel) often overwhelmed by the scale of the situation.

2.1.1. Emergency (relief) Logistics

Emergency logistics includes relief operations after disasters such as transferring affected people from affected areas and supplying all relief centers with commodities such as food, water, medical devices, etc. Research on emergency logistics has started since 1955. Two kinds of emergencies, namely daily and non-daily ones have been studied since 1980s (de la Torre et al. (2012)). For instance, medical emergencies, fire, or police responses can be classified as daily emergencies. On the other hand, “emergency response” (i.e., response to non-daily emergencies) consists of search, rescue, and evacuation operations in disasters or sudden catastrophe such as natural disasters. Based on the two-stage-emergency response, suggested by Tufekci and Wallace (1998) and Caunhye et al. (2012), operations in humanitarian logistics can be classified into before or after disaster ones. Pre-event or “pre-disaster” tasks include predicting and analyzing potential hazards and developing necessary operations plans for mitigation. Response to a disaster begins when the disaster has not finished yet and all tasks such as location, allocation, coordination, and management of available resources are considered in “post-event” or “post-disaster” operations. “Facility location” and “stock pre-positioning” are main examples of operations which are performed before disaster incident. On the other hand, the operations after disaster are evacuation or casualty transportation.

According to Altay and Green (2006) , Caunhye et al. (2012), “ESRI White Paper” (2008), and Kovács and Spens (2012), four phases emergency logistics incorporate Mitigation, Preparedness, Response, and Recovery as summarized in the following sub-sections. According to the first classification, mitigation and preparedness are pre-disaster operations while post-disaster operations include response and recovery to return to normality in the affected area:

2.1.1.1. Mitigation

Mitigation’s concentration is more on long term planning in order to reduce the damage that might occur by disasters. According to Altay and Green (2006), major activities in the mitigation phase can be summarized as follows:

- Zoning and land use controls to prevent occupation of high hazard areas
- Barrier construction to deflect disaster forces
- Active preventive measures to control developing situations
- Building codes to improve disaster resistance of structures
- Tax incentives or disincentives
- Controls on rebuilding after events
- Risk analysis to measure the potential for extreme hazards
- Insurance to reduce the financial impact of disasters

2.1.1.2. Preparedness

This phase involves planning all actions required to be done and preparing different parties when a disaster occurs. According to Altay and Green (2006) major activities in the preparedness phase can be summarized as follows:

- Recruiting personnel for the emergency services and for community volunteer groups
- Emergency planning
- Development of mutual aid agreements and memorandums of understanding
- Training for both response personnel and concerned citizens
- Threat-based public education
- Budgeting and acquiring vehicles and equipment
- Maintaining emergency supplies
- Construction of an emergency operations center
- Development of communications systems
- Conducting disaster exercises to train personnel and test capabilities

2.1.1.3. Response

In this phase, logisticians uses the resources and guidelines, planed in advance, to save people's lives, properties, and the environment and also to maintain the structure of the area. To do so, first level responders have to be provided by resources and emergency services. According to Altay and Green (2006) major activities in the response phase can be summarized as follows:

- Activating the emergency operations plan
- Activating the emergency operations center
- Evacuation of threatened populations
- Opening of shelters and provision of mass care
- Emergency rescue and medical care
- Fire fighting
- Urban search and rescue

- Facility location
- Relief distribution and casualty transportation
- Emergency infrastructure protection and recovery of lifeline services
- Fatality management

2.1.1.4. Recovery

All the operations that result in restoring the influenced area to the original state are considered in this phase. Recovery actions are divided into two parts with respect to essentiality of needs after a disaster, shot-term and long-term operations. Short-term action plans are made in case of immediate supports, while long-term recovery attempts are made to repair the infrastructure and rebuilding the society. According to Altay and Green (2006) major activities in the recovery phase can be summarized as follows:

- Disaster debris cleanup
- Financial assistance to individuals and governments
- Rebuilding of roads and bridges and key facilities
- Sustained mass care for displaced human and animal populations
- Reburial of displaced human remains
- Full restoration of lifeline services
- Mental health and pastoral care

2.2. Facility location/allocation in emergency logistic networks

In general, the problem of location/allocation of emergency facilities such as medical centers, temporary shelters, and aid-distribution warehouses aims to select among the existing facilities or to build new ones in order to allocate affected population or distribute aids to them within a specified response time such that the investment and transportation cost is minimized. In what follows, we confine our attention to the most recent contributions on relief facility location/allocation problem where the uncertainty inherent in natural disasters have been taken into consideration.

Jia et al. (2007a) suggest a framework for facility location of medical services by considering characteristics of large scale disasters. According to the authors, large scale catastrophes overwhelm small local responders; hence, they suggest to consider local storage centers in order to, first, store special equipment and then repackage them and distribute among all demand points.

They also propose set-covering, P-median, and P-center models in large scale emergency medical services by considering uncertainty in terms of percentage of available services from each facility as a result of post-disaster disruption of roads and facilities. Finally, the effectiveness of proposed models are validated in three types of terrorist attacks.

Mete and Zabinsky (2010) develop a two-stage stochastic medical supply location/allocation model that is applicable in the context of interdisciplinary agencies in charge of pre-disaster planning in humanitarian logistic networks. In the aforementioned model, the first stage decisions are related to the location of warehouses along with the inventory level of medical supplies required after disaster; whereas second-stage decisions deal with distribution of medical aids from warehouses to affected population in demand zones under different post-disaster demand scenarios. The authors test their model in the context of an earthquake in Seattle City.

In Jia et al. (2007b), the same authors develop three solution approaches including Genetic Algorithm, Locate-Allocate heuristic, and a Lagrangian Relaxation algorithm for solving the stochastic maximal covering problem proposed in Jia et al. (2007a). Their experimental results indicate that Lagrangian Relaxation and LocAlloc heuristics generate better solutions in less computational time comparing to Genetic algorithm.

Salmeron and Apte (2010) investigate the problem of assets prepositioning in the context of natural disasters. They propose a two-stage stochastic optimization model that in first-stage, decides on the expansion level of various rescue resources such as warehouses, medical centers, ramp space, and shelters. Second-stage decisions, on the other hand, are related to logistics of the problem, i.e., deploying allocated resources and contracted transportation assets to rescue critical population (in need of emergency evacuation), deliver required commodities to stay-back population, and transport the transfer population displaced by the disaster. The objective function is to minimize the expected number of casualties among the first two groups of affected population in addition to the number of population in the last category that could not be transported. The proposed model is tested in the context of hurricanes by considering six affected areas and relief locations under five possible scenarios.

With the goal of increasing preparedness for natural disasters, Rawls and Turnquist (2010) propose a two-stage stochastic mixed integer programming model for pre-positioning of emergency supplies under uncertainty in demand and availability of the transportation network. The proposed model aims to identify the warehouse location as well as stock level of various items in each location as the first stage decision. On the other side, the amount of transported aids to areas affected by disaster, part of commodities which remains unused, and the amount of unmet demand constitute second-stage decisions under various demand scenarios. The authors propose a Lagrangian L-Shape algorithm to solve the above-mentioned model. They also provide a hurricane case study in a coastal area in the southern United States.

Rawls and Turnquist (2012) extend the model proposed in Rawls and Turnquist (2010) in a dynamic setting, in order to satisfy short-term demands (over approximately the first 72 h) for emergency supplies under uncertainty about what demands will have to be met and where those demands will occur. The authors propose a two-stage stochastic model that decides on the optimal location of shelters as the first-stage decision. The second-stage decisions incorporate the distribution of medical supplies to shelters according to the arrival of evacuees over the 72h planning horizon which is divided to 12h time intervals. They also consider a probabilistic constraint in order to satisfy the demand at a given percentage of all demand scenarios. The proposed model was validated for a hurricane case in North Carolina, USA.

Noyan (2012) extends the disaster preparedness management model proposed by Rawls and Turnquist (2010) by including a risk measure, Conditional- Value-at-Risk (CVaR) as the risk measure in the objective function of the two-stage stochastic model. The idea is to protect the total cost of the preparedness plan over a set of worst-case scenarios at a certain confidence level. Two variants of Benders Decomposition algorithms, namely single-cut and multi-cut ones, are also proposed to efficiently solve the resulting robust optimization model.

Lu and Sheu (2013) propose a robust P-center model for the location/allocation of urgent relief distribution centers under uncertain post-disaster travel times. The objective is to minimize the worst-case deviation of maximum travel time between urgent relief distribution centers and demand points from optimal value. A local-search heuristic based on simulated-annealing algorithm is also developed to solve the proposed model. The authors validate their proposed model and solution algorithm on a real case study, i.e., Jiji earthquake, stroke the central part of Taiwan in 1999.

2.3. Summary of relevant literature

Our survey on the existing literature published after 2007 indicate that the majority of articles related to disaster preparedness planning are mainly focused on location/allocation of medical centers or humanitarian supply facilities. In contrary, shelter location and population evacuation planning in the context of earthquakes has been less investigated in the literature. Furthermore, classical set-covering, P-median, or P-center models are usually used for problem formulation. Two-stage stochastic programming approach is the most popular tool in order to incorporate the uncertain behavior of natural disasters into such decision models. Hence, except from a couple of models where risk measures are included in their objective function, the majority of proposed models deal with minimizing the expected cost of the plan over a set of scenarios. Regarding the high level of uncertainty in terms of frequency, location, and magnitude of natural disasters, minimizing some risk measures seems to be essential in order to protect the plan against extreme cases. Finally, in all of the reviewed two-stage stochastic facility location/allocation models, the first-stage decision is related to the location of open facilities while second-stage (recourse) decisions deal with the distribution of supplies from facilities to demand points. In other words, despite the possibility of unavailability of some facilities after disaster, post-disaster facility location (probably at a higher cost) has not been considered as a recourse action in the aforementioned models.

In this thesis, we aim to fill the aforementioned gaps by proposing different variants of shelter location/allocation problem in the context of earthquakes. Two-stage stochastic programming and robust optimization approaches are applied in order to formulate this problem under uncertainty in terms of the number of population who need to be evacuated in addition to the availability of transportation network and open shelters after earthquake attack.

Chapter 3: Methodology

In this section, a brief description of the main methodologies, namely two-stage stochastic programming (Birge and Louveaux (2011)) and robust optimization (Rockafellar and Uryasev (2000); Schultz and Tiedemann (2006)), adopted in order to solve shelter location/allocation problem in humanitarian logistics networks are provided.

3.1. Two-Stage Stochastic programming with recourse

Consider the following uncertain linear programming model:

$$Min\ Z = c^T x, \tag{1}$$

Subject to:

$$Ax = b, \tag{2}$$

$$T(\omega)x \geq h^T(\omega), \tag{3}$$

$$x \geq 0, \tag{4}$$

where ω is the vector of random parameters, $T(\omega)$ and $h(\omega)$ are random technological coefficient matrix and right-hand side vector, respectively. In the above model, constraints (2) and (3) represent the set of deterministic and stochastic constraints, respectively. In two-stage stochastic models, we explicitly classify the decision variables according to whether they are implemented before or after an outcome of the random variables is observed. In other words, we have a set of decisions to be taken without full information on the random parameters. These decisions are called first-stage decisions, and are usually represented by a vector (x). Later, full information is received on realizations (scenarios) of some random vector ω. Then, second-stage or recourse actions (y) are taken. These second-stage decisions allow us to model a response to each of the observed outcomes (scenarios) of the random variables, which constitutes our corrective (recourse) action. In general, this response will also depend upon the first-stage decisions. In mathematical programming terms, this defines the so-called two-stage stochastic program with recourse of the form:

$$Min\ Z = c^T x + E_\omega[Q(x, \omega)], \tag{5}$$

Subject to:

$$Ax = b, \tag{6}$$

$$x \geq 0, \tag{7}$$

where $Q(x, \omega) = min\{q^T(\omega)y | Wy = h^T(\omega) - T(\omega)x\}$, W is the recourse matrix, $q^T(\omega)$ is the vector of penalty cost of second-stage (recourse) variables, and E_ω denotes mathematical expectation with respect to ω.

In the case of continuous distribution for random variables in model (5)-(7), the calculation of the expected value $E_\omega[Q(x, \omega)]$ requires the calculation of multiple integrals with respect to the measure describing the distribution of ω. The computational effort increases with the dimension of the stochastic variables vector and this leads to tremendous amount of work. On the other hand, if ω can be represented as a set of discrete scenarios s (i.e., it has a finite discrete distribution (s, p_s)), then (5)-(7) can be transformed into its *deterministic equivalent* which is an ordinary linear program as follows:

$$Minimize\ c^T x + \sum_{s=1}^{S} p_s q^T y_s \tag{8}$$

Subject to:

$$T_s x + W y_s = h_s, \qquad s = 1, \dots, S, \tag{9}$$

$$x, y_s \geq 0, \qquad s = 1, \dots, S, \tag{10}$$

where T_s, h_s, y_s denote, respectively, constraint coefficients matrix, right-hand-side vector, and the vector of second-stage decisions under scenario s and p_s denotes the probability of scenario s.

3.1.1.1. The expected value of perfect information (EVPI)

The maximum amount that a decision maker will pay willing to know the whole information about the future is considered as expected value of perfect information (EVPI) (Birge and Louveaux (2011)) and is calculated as follows:

Consider the following model as the optimization problem associated with one particular scenario ω (scenario sub problem):

$$\min_{x \in X: Ax = b} z(x, \omega) = \left\{ c^T x + \min_{y \in Y} \{ q^T y(\omega) : Wy(\omega) = h(\omega) - T(\omega)x \} \right\} \tag{11}$$

We assume that we can find the optimal solution of the above model for all scenarios. We denote the optimal solution of the above model and its objective value as $\overline{x}(\omega)$, and $z(\overline{x}(\omega), \omega)$, respectively.

We calculate the expected value of the optimal solution (wait-and-see (WS) solution) as follows:

$$WS = E_\omega \left[\min_x z(x, \omega) \right] = E_\omega [z(\overline{x}(\omega), \omega)] \tag{12}$$

The *EVPI* is the difference between the wait-and-see solution and the here-and-now solution corresponding to the recourse problem (*RP*)

$$RP = \min_x E_\omega [z(x, \omega)] \tag{13}$$

$$EVPI = RP - WS \tag{14}$$

3.1.1.2. The Value of the stochastic solution (VSS)

The value of the stochastic solution (VSS) evaluates the solution of the two-stage stochastic model through comparing it with the solution of mean-value or expected-value (EV) problem. We denote the expected value problem as:

$$EV = \min_{x} z(x, \overline{\omega}) \tag{15}$$

where $\overline{\omega} = E(\omega)$. We also denote the optimal solution of the EV model as $\overline{x}(\overline{\omega})$. We then define the expected result of using the EV solution (EEV) to be

$$EEV = E_{\omega}[z(\overline{x}(\overline{\omega}), \omega)] \tag{16}$$

The EEV measures how $\overline{x}(\overline{\omega})$ performs, allowing second-stage decisions to be chosen optimally as functions of $\overline{x}(\overline{\omega})$ and ω.

The value of the stochastic solution can be defined as

$$VSS = EEV - RP \tag{17}$$

3.1.2. Robust optimization of two-stage stochastic programs

Two-stage stochastic programming approach focuses on optimizing the expected performance (e.g., minimizing the expected cost) over a range of possible scenarios for the random parameters. Hence, we can expect that the system would behave optimally in the mean sense if the stochastic programming model solution is implemented. However, the system might perform poorly at a particular realization of scenarios, such as the worst-case scenario. This means that the stochastic model cannot reflect the variability of performances for each scenario realization and it might yield solutions that are not very robust.

The robust optimization (RO) method developed by Mulvey et al. (1995) extend stochastic programming with the introduction of risk measures (robustness criteria), such as Conditional-value-at-Risk (CVaR) in the objective function. In this section, we confine our attention to robust optimization models with CVaR as the robustness criterion.

"Value-at-Risk (VaR)" is the maximum loss in terms of the objective function with a specified confidence level α. Conditional Value-at-Risk (CVaR) is also called mean excess loss or Tail-VaR. It measures the expected value of the loss in the $(1-\alpha)\%$ worst cases as also illustrated in Figure 1. Unlike VaR, using CVaR as the variability (risk) measure in 2-stage stochastic programs leads to convex and tractable deterministic equivalent models (Rockafellar and Uryasev (2000); Schultz and Tiedemann (2006)).

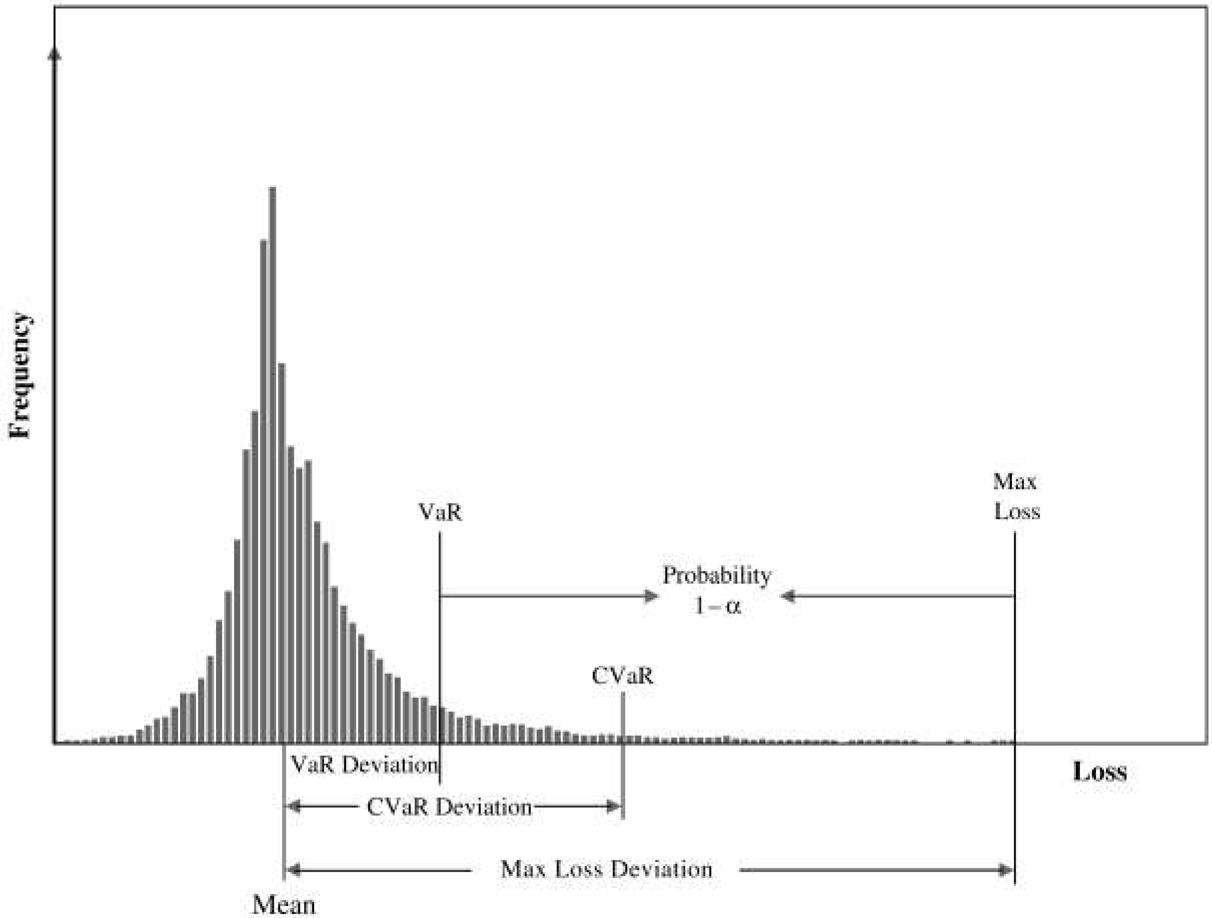

Figure 1: CVaR and VaR (adopted from Sarykalin et al. (2008)*)*

Let's consider a cost minimization framework. Consider a family of real random cost variables $\{Z(x,\omega)\}_{x\in X}$ on a probability space (Ω, A, P). We are looking to minimize the expected value of the costs in the $(1-\alpha)\%$ worst cases, where $\alpha \in (0,1)$ is a preselected probability. This value could be called α Conditional Value-at-Risk.

Definition: for $Z(x,\omega)$ and a preselected probability $\alpha \in (0,1)$, we define the following:

a) The distribution function: $\Psi(x,\eta) \coloneqq P(\{\omega \in \Omega : Z(x,\omega) \leq \eta\})$

b) The α-Value-at-Risk (α-VaR): $\eta_\alpha(x) \coloneqq min\{\eta : \Psi(x,\eta) \geq \alpha\}$

c) The α-Value-at-Risk$^+$ (α-VaR$^+$): $\eta_\alpha^+(x) \coloneqq min\{\eta: \Psi(x,\eta) > \alpha\}$

d) The α -CVaR: $\phi_\alpha(x) \coloneqq$ mean of the α-tail distribution of $Z(x,\omega)$

Where the distribution in question is the one with the distribution function $\Psi(x,\eta)$ defined by:

$$\Psi_\alpha(x,\eta) := \begin{cases} 0, & for\ \ \eta < \eta_\alpha(x) \\ \dfrac{[\Psi(x,\eta)-\alpha]}{[1-\alpha]}, & for\ \ \eta \geq \eta_\alpha(x) \end{cases} \tag{18}$$

Proposition: for $Z(x,\omega)$, the α-CVaR can be expressed by the following minimization formula:

$$\phi_\alpha(x) \coloneqq \min_{\eta \in R} f(\alpha,\eta,x) \tag{19}$$

Where

$$f(\alpha,\eta,x) \coloneqq \eta + \frac{1}{1-\alpha} E\{max\{Z(x,\omega)-\eta,0\}\} \tag{20}$$

As it was stated before $f(\alpha,\eta,x)$ is convex and finite and as a result continues.

3.1.2.1. Two-stage stochastic programs with CVaR robustness criterion

Now the two-stage stochastic programming model (8)-(10) by considering CVaR criterion can be presented as follows:

$$Min\ Z = c^T x + \sum_{s=1}^{S} p_s q^T y_s + \lambda \left[\eta + \frac{1}{1-\alpha}\sum_{s=1}^{S} p_s z_s^+\right] \tag{21}$$

Subject to:

$$T_s x + W y_s = h_s \qquad s = 1, \dots, S \tag{22}$$

$$z_s^+ \geq c^T x + \sum_{s=1}^{S} p_s q^T y_s - \eta \qquad s = 1, \dots, S \tag{23}$$

$$x, y_s, z_s^+ \geq 0 \qquad s = 1, \dots, S \tag{24}$$

Where $\lambda \geq 0$ a weight factor that reflect the decision maker's risk awareness level. It can be observed that the above formulation leads to a convex optimization model that minimizes simultaneously α-VaR (η) and α-CVaR.

Chapter 4: Problem description and formulation

In this chapter we first describe the problem under investigation. Then, we formulate the problem under different assumptions in both deterministic and stochastic contexts.

4.1. Problem description

In this thesis, we investigate the shelter location/allocation problem in humanitarian logistics networks (HLNs) corresponding to natural disasters with a particular focus on earthquakes. Considering a region that can be affected by an earthquake, there are certain safe zones that are suitable for building shelters. After each earthquake, the population of distinct areas, especially those who live in the vicinity of the faults could be affected; hence they need to be evacuated from the affected areas and transported to shelters. The severity of the impact depends on the population density, housing density, as well as the structure of houses in the affected areas, the epicentre, and the magnitude of the earthquake. Because the affected population are distributed all around the area under investigation, some demand zones such as hospitals should be designated for each area. Finding the location of shelters in addition to the allocation of demand zones to shelters such that the evacuation is carried out within 72h after the earthquake at the minimum cost are amongst challenging decisions in HLNs. Furthermore, the uncertainty inherent in the epicenter and magnitude of earthquakes result in uncertainty in the number of affected population (demand) and availability of roads and shelters. The latter uncertain factors would further complicate the on-time evacuation of population in affected areas.

In what follows, we first formulate two variants of shelter location/allocation problem in a deterministic context. Next, we incorporate the uncertainty inherent in the epicenter and magnitude of the earthquake into those models. Subsequently, we propose two-stage stochastic programming and one robust optimization model to formulate this problem in an uncertain context.

4.2. Problem formulation

4.2.1. Deterministic shelter location /allocation models in HLNs

Inspiring from the literature on facility location/allocation problem, the shelter location/allocation problem in a deterministic context can be formulated as two different models (model 1 and 2). In the first model (classical model in the literature), the decision variables incorporate the location of shelters and the assignment of each demand zone to one shelter such that all demand zones are assigned to shelters within the allowable evacuation time (e.g., 72h after the earthquake) and the shelter capacities are satisfied. The objective is to minimize the cost of shelter installation and transportation of population from demand zones to shelters. In order to make model 1 more realistic, we propose an alternative model (model 2) that identifies the location of shelters and the number of people that can be transported from various demand zones to different shelters within the given evacuation time. This model will provide the possibility of identifying the number of affected population that cannot be evacuated on time due to restricted/ reduced capacity of shelters and/or unavailability of roads. This alternative formulation is particularly useful while dealing with various sources of uncertainty mentioned earlier. The above-mentioned models are formulated as follows:

4.2.1.1. Model 1

The following notations are used to formulate the shelter location/allocation problem:

Notation

Sets:

We consider a set of demand zones $i \in I$ and a set of shelter locations $j \in J$.

Parameters:

T_{ij}: Time (minutes) to transport population from the demand zone i to shelter j

d_i: Number of affected population in demand zone i

CAP_j: Shelter capacity at location j,

P: Maximum number of potential locations for shelters,

E: Maximum allowable evacuation time (e.g. 72 h = 4320 minutes),

$$a_{ij} = \begin{cases} 1, & \text{if population of demand zone } i \text{ can be transported to shelter } j, \\ 0, & \text{Otherwise (the link } (i,j) \text{ is not available),} \end{cases}$$

σ: Number of people that can be transported by each vehicle,

W_{ij}: Transportation cost ($/minute) from demand zone i to shelter j.

Decision variables

$$y_j = \begin{cases} 1 & \text{if a shelter is built at location } j, \\ 0 & \text{Otherwise,} \end{cases}$$

$$x_{ij} = \begin{cases} 1 & \text{if the affected population at demand zone } i \text{ is assigned to shelter } j, \\ 0 & \text{Otherwise,} \end{cases}$$

Mathematical programming model:

$$Min\ Z = \sum_j f_j y_j + \sum_i \sum_j W_{ij} \frac{d_i}{\sigma} x_{ij} \tag{25}$$

Subject to:

$$\sum_j a_{ij} x_{ij} = 1 \qquad \forall i \tag{26}$$

$$\sum_j y_j \le P \tag{27}$$

$$\sum_i d_i x_{ij} \le CAP_j c_j y_j \qquad \forall j \tag{28}$$

$$T_{ij} \frac{d_i}{\sigma} x_{ij} \le E \qquad \forall i, \forall j \tag{29}$$

$$y_j \in \{0,1\} \qquad \forall j \qquad (30)$$

$$x_{ij} \in \{0,1\} \qquad \forall i, \forall j \qquad (31)$$

The objective function (25) minimizes the cost of opening shelters and transportation of population from demand zones to shelters. Constraint (26) forces each demand zone to be assigned to only one shelter location in case of road availability. Constraint (27) states that the number of open shelters could be at most P. Constraint (28) is defined to ensure the demand zone assigned to an open shelter satisfy shelter's capacity. According to the literature, the evacuation operation should be done in at most 72 hours from the occurrence of an earthquake. Hence, we consider constraint (29) to make sure this requirement is taken into consideration. It is worth noting that this classical model in the literature is quite restrictive in the sense that it does not consider the possibility of transporting population in a given demand zone to different shelters in case of unavailability of shelters and/or roads. Also, it does not consider the possibility that part of affected population in a demand zone cannot be evacuated within 72 h after earthquake for similar reasons. The alternative formulation provided in the next sub-section (model 2) is a more realistic formulation that tries to circumvent the abovementioned limitations in model 1.

4.2.1.2. Model 2

The following extra notations are considered in order to formulate model 2.

c_j: Usable portion of shelter j,

d_i: Number of affected population in demand zone i,

L: Cost of leaving affected population at demand zones (injury penalty),

U_i: Number of people left at demand zone i.

Decision variables

x_{ij}: Number of transported people to shelter location j from demand zone i.

Mathematical programming model:

$$Min\ Z = \sum_j f_j y_j + \sum_i \sum_j W_{ij} \frac{x_{ij}}{\sigma} + \sum_i LU_i \tag{32}$$

Subject to:

$$\sum_j a_{ij} x_{ij} + U_i = d_i \qquad \forall i \tag{33}$$

$$\sum_j y_j \leq P \tag{34}$$

$$\sum_i x_{ij} \leq CAP_j c_j y_j \qquad \forall j \tag{35}$$

$$T_{ij} \frac{x_{ij}}{\sigma} \leq E \qquad \forall i, \forall j \tag{36}$$

$$y_j \in \{0, 1\} \qquad \forall j \tag{37}$$

$$x_{ij} \geq 0 \qquad \forall i, \forall j \tag{38}$$

The objective function (32) minimizes the cost of opening shelters, transporting affected population at demand zones to shelters, and the cost of leaving part of affected population at demand zones (due to lack of resources, shelters, and/or roads). Constraint (33) is a demand satisfaction constraint. It calculates the number of population who cannot be evacuated within 72h after earthquake. Constraint (34) limits the number of open shelters to at most P. Constraint (35) indicates that the number of affected population at various demand zones transported to each shelter should not exceed shelter's capacity. The constraint (36) make sure evacuation is carried out within 72 h after earthquake.

4.2.2. Shelter location/allocation in HLNs Under uncertainty

In this section, we incorporate the uncertainty inherent in the epicenter and magnitude of the earthquake into the two deterministic shelter location/allocation models formulated in 4.2.1. In what follows, we propose two-stage stochastic programming and robust optimization formulations for this problem.

4.2.2.1. Two-stage stochastic models for shelter location/allocation problem in HLNs

In this section, we first reformulate shelter location/allocation model 1 ((25)-(31)) under uncertainty, for which we provide two alternative two-stage stochastic programming models which differ in terms of corrective (recourse) actions in the presence of uncertainty. Next, we provide the two-stage stochastic programming reformulation of shelter location/allocation model 2 ((32)-(38)).

4.2.2.1.1. Classical two-stage stochastic formulation for model 1

In this section, we reformulate shelter location/allocation model 1 (model (25)-(31)) under uncertainty in the epicenter and magnitude of earthquake by considering one type of corrective (recourse) action. Accordingly, the first stage decision identifies the optimal location of shelters. This decision is a here-and-now decision which must be taken without any information on the earthquake. The second-stage decision, which is a corrective (recourse) action, deals with the allocation of demand zones to each open shelter after the earthquake strikes. Hence, it must be defined for each earthquake scenario. The latter scenario identifies the number of population affected in different demand zones in addition to the availability of roads and shelters after each earthquake. The objective is to minimize the fixed cost of opening shelters in addition to the expected cost incurred for transporting affected population from demand zones to shelters. The following notations are used to formulate two-stage stochastic classical shelter location/allocation model in addition to those previously defined.

c_j^s: Availability of shelter j under scenario s: $c_j^s = \begin{cases} 1, & \text{Shelter } j \text{ is available under scenario } s \\ 0, & \text{Otherwise} \end{cases}$

T_{ij}^s: Time it takes to transport affected population from demand zone i to shelter j (per person) under scenario s (T_{ij}^s takes a large number if (i,j) is destroyed) (min)

d_i^s: Number of affected population in demand zone i under scenario s

CAP_j^s: Capacity of shelter j under scenario s

p_r^s: Probability of scenario s

$$a_{ij}^s = \begin{cases} 1, & \text{if population of demnad zone } i \text{ can be transported} \\ & \quad\quad t\text{o shelter } j \text{ under scenario } s \\ 0, & \quad\quad \text{Otherwise (the link } (i,j) \text{ is not available)} \end{cases}$$

W_{ij}^s: Cost of transportation (per person) from demand zone i to shelter j under scenario s

$$x_{ij}^s = \begin{cases} 1 & \text{if the affected population at demand zone } i \text{ is} \\ & \quad \text{assigned to shelter } j \text{ under scenario } s \\ 0 & \text{Otherwise} \end{cases}$$

Two-stage stochastic classical model

$$Min\ Z = \sum_j f_j y_j + \sum_i \sum_j \sum_s p_r^s W_{ij}^s \frac{d_i^s}{\sigma} x_{ij}^s \qquad (39)$$

Subject to:

$$\sum_j a_{ij}^s x_{ij}^s = 1 \qquad \forall i, \forall s \qquad (40)$$

$$\sum_j y_j \leq P \qquad \forall s \qquad (41)$$

$$\sum_i d_i^s x_{ij}^s \leq CAP_j^s c_j^s y_j \qquad \forall j, \forall s \qquad (42)$$

$$T_{ij}^s \frac{d_i^s}{\sigma} x_{ij}^s \leq E \qquad \forall i, \forall j, \forall s \qquad (43)$$

$$y_j \in \{0,1\} \qquad \forall j \qquad (44)$$

$$x_{ij}^s \in \{0,1\} \qquad \forall i, \forall j, \forall s \qquad (45)$$

Constraints of model (39)-(45) are similar to those defined in model 1 except that they are defined for all earthquake scenarios.

4.2.2.1.2. Alternative two-stage stochastic formulation for model 1

An alternative two-stage stochastic reformulation of shelter location/allocation model 1 ((25)-(31)) is provided in this section that differs from the classical two-stage stochastic model in terms of corrective (recourse) actions. The idea is to consider the possibility of opening new shelters after the earthquake at a higher cost as a second type of recourse action. Regarding the fact that extra shelters are only required under high-impact earthquakes, the goal is to reduce the number (cost) of shelters that must be opened in the first-stage comparing to classical two-stage stochastic model, where more shelters might be opened in the first-stage in order to guarantee the full evacuation of population in demand zones under all earthquake scenarios. The following additional notations are used to formulate this model:

$f_j'(\gg f_j)$: Fixed cost of opening a shelter at j after the earthquake (e.g., leasing a place)

$$z_j^s = \begin{cases} 1 & \text{if a shelter is opened at } j \text{ after} \\ & \quad \text{the earthquake at } j \text{ under scenario } s \\ 0 & \text{Otherwise} \end{cases}$$

Alternative two-stage stochastic model 1

$$Min\ Z = \sum_j f_j y_j + \sum_j \sum_s p_r^s f_j' z_j^s + \sum_i \sum_j \sum_s p_r^s W_{ij}^s \frac{d_i^s}{\sigma} x_{ij}^s \tag{46}$$

Subject to:

$$\sum_j a_{ij}^s x_{ij}^s = 1 \qquad \forall i, \forall s \tag{47}$$

$$\sum_j (y_j + z_j^s) \leq P \qquad \forall s \tag{48}$$

$$\sum_i d_i^s x_{ij}^s \leq CAP_j^s c_j^s \left(y_j + z_j^s\right) \qquad \forall j, \forall s \tag{49}$$

$$y_j + z_j^s \leq 1 \qquad \forall j, \forall s \tag{50}$$

$$T_{ij}^s \frac{d_i^s}{\sigma} x_{ij}^s \leq E \qquad \forall i, \forall j, \forall s \tag{51}$$

$$y_j \in \{0, 1\} \qquad \forall j \qquad (52)$$

$$x_{ij}^s \in \{0, 1\} \qquad \forall i, \forall j, \forall s \qquad (53)$$

$$z_j^s \in \{0, 1\} \qquad \forall j, \forall s \qquad (54)$$

Constraints of model (46)-(54) are similar to those defined in model (39)-(45), except for constraints (48)-(50). Constraint (48) limits the number of shelters that can be opened before and after earthquake, while constraint (49) limits the number of people that can be assigned to shelters, opened before or after earthquake, by considering shelter capacities. Finally, constraint (50) indicates that at any candidate location, a shelter can be either opened before or after the earthquake.

4.2.2.1.3. Two-stage stochastic Model 2

In this Section, we provide the reformulation of shelter location/allocation model 2 ((32)-(38)) under uncertainty. In this model, the first stage decision variable identifies the location of shelters that must be opened without having any information on the epicenter and magnitude of earthquake. The second-stage decisions incorporate: *i*) the location of shelters that must be opened after the earthquake attack; *ii*) the number of population from each demand zone that must be transported to each shelter; and *iii*) the number of affected population that cannot be transported to shelters within 72h after earthquake under different scenarios. The objective is to minimize the expected cost of the abovementioned decisions. The following additional notations are used to formulate two-stage stochastic model 2:

c_j^s: Usable portion of shelter j under scenario s (percent),

Decision variables

x_{ij}^s: Number of transported people to shelter location j from center i,

U_i^s: Number of not-transported people left at demand zone ,

Two-stage stochastic model 2:

$$Min\ Z = \sum_j f_j y_j + \sum_j \sum_s p_r^s f_j' z_j^s + \sum_i \sum_j \sum_s p_r^s W_{ij}^s \frac{x_{ij}^s}{\sigma} + \sum_i \sum_s p_r^s L U_i^s \qquad (55)$$

Subject to:

$$\sum_j a_{ij}^s x_{ij}^s + U_i^s = d_i^s \qquad \forall i, \forall s \qquad (56)$$

$$\sum_j (y_j + z_j^s) \leq P \qquad \forall s \qquad (57)$$

$$\sum_i x_{ij}^s \leq CAP_j^s c_j^s (y_j + z_j^s) \qquad \forall j, \forall s \qquad (58)$$

$$y_j + z_j^s \leq 1 \qquad \forall j, \forall s \qquad (59)$$

$$T_{ij}^s \frac{x_{ij}^s}{\sigma} \leq E \qquad \forall i, \forall j, \forall s \qquad (60)$$

$$y_j \in \{0, 1\} \qquad \forall j \qquad (61)$$

$$x_{ij}^s \geq 0 \qquad \forall i, \forall j, \forall s \qquad (62)$$

$$z_j^s \in \{0, 1\} \qquad \forall j, \forall s \qquad (63)$$

Constraints (56)-(63) are similar to constraints of model (32)-(38) except that they are defined for each earthquake scenario. Also, constraints (57)-(59) are also similar to constraints (48)-(50) in model (46)-(54).

4.2.2.2. Robust optimization model (Conditional Value at Risk (CVaR))

The two-stage stochastic model 2 ((55)-(63)) aims for identifying the location of shelters before the earthquake strikes such that the expected cost of opening new shelters after earthquake, the population transportation cost, as well as the cost of leaving part of affected population in demand zones is minimized. Hence, it is expected that the proposed solution is effective in the mean sense. Nonetheless, it is possible that implementing the solution of this model lead to a very large number of affected population left non-evacuated in demand zones under certain scenarios (e.g., worst-case scenario). In order to protect the shelter location/allocation plan under such extreme earthquake scenarios, a robustness criterion can be added to the objective function of two-stage stochastic model 2. In this study, we choose Conditional Value-at-Risk (CVaR) as the robustness criterion due to the importance of solution robustness at a certain confidence level in the context of earthquakes. Given the probabilistic nature of earthquake scenarios, in the context of shelter location/allocation problem under investigation, Value-at-Risk (VaR) can be interpreted as the maximum cost incurred by leaving part of affected population in demand zones at a certain confidence level α. Conditional Value-at-Risk (CVaR) then can be interpreted as the mean excess cost incurred by leaving part of affected population in demand zones in the $(1-\alpha)\%$ worst cases (i.e., at $(1-\alpha)\%$ tail-VaR). Finally, in order to take into account the trade-off between the expected cost and the robustness criterion (CVar), a goal programming coefficient $\lambda \geq 0$ is considered in the objective function of the robust optimization model. This parameter reflects the risk awareness level of the decision maker. The following extra notations are used to formulate robust shelter location/allocation model.

η: Maximum cost incurred for leaving part of affected population in demand zones at $\alpha\%$ confidence level (VaR),

ϕ^s: The cost incurred for leaving part of affected population in demand zones that exceeds η,

$$Min\ Z = \sum_j f_j y_j + \sum_j \sum_s p_r^s f_j' z_j^s + \sum_i \sum_j \sum_s p_r^s W_{ij}^s \frac{x_{ij}^s}{\sigma} + \sum_i \sum_s p_r^s L U_i^s + \lambda \left[\eta + \frac{1}{1-\alpha} \left[\sum_s p_r^s \phi^s \right] \right] \tag{64}$$

Subject to:

$$\sum_j a_{ij}^s x_{ij}^s + U_i^s = d_i^s \qquad \forall i, \forall s \tag{65}$$

$$\sum_j (y_j + z_j^s) \leq P \qquad \forall s \tag{66}$$

$$\sum_i x_{ij}^s \leq CAP_j^s c_j^s (y_j + z_j^s) \qquad \forall j, \forall s \tag{67}$$

$$y_j + z_j^s \leq 1 \qquad \forall j, \forall s \tag{68}$$

$$T_{ij}^{s}\frac{x_{ij}^{s}}{\sigma} \leq E \qquad \forall i, \forall j, \forall s \qquad (69)$$

$$\phi^{s} \geq \sum_{i} LU_{i}^{s} - \eta \qquad \forall s \qquad (70)$$

$$y_j \in \{0, 1\} \qquad \forall j \qquad (71)$$

$$x_{ij}^{s} \geq 0 \qquad \forall i, \forall j, \forall s \qquad (72)$$

$$z_j^{s} \in \{0, 1\} \qquad \forall j, \forall s \qquad (73)$$

$$\phi^{s} \geq 0 \qquad \forall s \qquad (74)$$

$$\eta \geq 0 \qquad (75)$$

The last term in the objective function formulates the robustness criterion described above. Constraints of model (64)-(75) are similar to those described in two-stage stochastic model (55)-(63) except for constraint (70). It calculates the number of affected population left in demand zones that exceeds the maximum number of non-evacuated population at α% confidence level.

Chapter 5: Experimental result

In this chapter, we first describe a case study considered in this thesis for validating stochastic and robust shelter location/allocation models proposed in Chapter 4. Then, we present the computational result related to the above-mentioned models. The objective is also to draw a comparison between deterministic, stochastic, and robust optimization models. We used a commercial solver, CPLEX (version 12.4), to solve all models on a personal computer with a Dual-Core, 2.8 GHz Processor, 4 GB RAM and 64-bit Operation System.

5.1. Case data

It is noteworthy that tremendous effort has been made to gather relevant data for the case study. Most of the data gathered are real data inspired from Mete and Zabinsky (2010) except for some coefficients that are changed based on each geographic area's specifications. We study Seattle and Cascadia faults as the case study. This area is located between Puget Sound and Lake Washington on hilly land in western Washington as demonstrated in Figure 2. In what follows, we provide more details on how different parameters related to models provided in Chapter 4 are generated. The data are provided respectively for shelter locations, demand zones, and the transportation network features under deterministic and stochastic conditions.

Figure 2: Cascadia subduction zone

5.1.1. Shelter locations

In this case study, five candidate locations are considered for building shelters to which evacuated population from demand zones can be transported and housed. These locations are chosen amongst those with the smallest chance of earthquake occurrence. The fixed cost of opening these shelters is extracted from Mete and Zabinsky (2010). The fixed cost of opening a shelter after earthquake strikes is considered as one and half of the cost incurred before the earthquake. The amount of such increased cost depends on the availability of undestroyed areas as well as the amount of resources required to prepare those areas for housing evacuated population.

In order to estimate the capacity of each shelter, first we figure out how many medical tents can be located in the given shelter and how many people can be sheltered in each type of medical tent. Then by multiplying the capacity of tents (person) to the number of tents we reach the nominal (deterministic) capacity of the shelters. The capacity of all shelter locations for different models are provided in Table 22, Table 26, and Table 32 in Appendix.

The range of capacity of shelters is variable between 6,000 and 11,000 people in deterministic and stochastic models 1 and models (25)-(31) and (39)-(54). In stochastic models, depending on the epicenter and magnitude of the earthquake, we consider two situations: 1) the shelter is available at full capacity or not available at all (model 1 (39)-(54)); or 2) a percentage of maximum capacity of shelters is considered to be available after earthquake (models (32)-(38) and (55)-(63)). In the latter case, the range of capacity of shelters after earthquake under different scenarios varies between 900 and 11,002 people.

5.1.2. Demand zones

We consider 10 possible locations as demand zones that can be affected by the earthquake in Seattle city. They represent demand zones in the city such as hospitals or other emergency centers. The demand at these zones represent a portion of the population who live in a given vicinity of such demand zones and are affected by the earthquake. We are assuming that the population of various areas in Seattle City are aware of the existence of such centers. In the context of stochastic shelter location/allocation models, we introduce different scenarios for the demand of the above-mentioned zones. Such scenarios are defined according to the epicenter and the impact of the earthquake on different areas of the city. The demand data in this case study are extracted from Altay and Green (2006) and are provided in Table 17 in Appendix. In the tables of the Appendix, the demand values are denoted as HS and HC when a high impact earthquake occurs in the Seattle fault and Cascadia area, respectively. Also, average and low impact earthquakes in Seattle and Cascadia faults are denoted as AS, AC, LS, and LC, respectively.

Considering what time of the day an earthquake might strike (working hours (W), rush hours (R), and non-working hours (N)), its impact (high, average, low), and the epicenter (Seattle or Cascadia) we define 18 scenarios for the demand as illustrated in Table 17 in the Appendix. According to Mazzotti and Adams (2004) the likelihood of occurrence of an earthquake with high impact in next 50 years is around 10 percent. On the other hand, the chance of occurrence of average and low impact earthquakes in this area is around 40% and 50%, respectively (GREW

(2005); Stewart (2005)). We assume that probabilities of occurrence of an earthquake in Seattle and Cascadia faults are 0.4 and 0.6 based on historical data in that area (Mete and Zabinsky (2010)). We also consider 30 rush hours, 48 working hours, and 90 non-working hours in one week with the probability of 0.175, 0.275, and 0.550, respectively. An earthquake with high or average impact, regardless the type of fault, result in more significant demand and devastation than a low impact one in the city. Hence, the likelihood of occurrence of earthquakes in scenarios are demonstrated in Table 15.

5.1.3. Transportation network

As demonstrated in Figure 3, there exist several routes between demand zones and shelter locations. These routes might be influenced by the earthquake and destroyed completely or partially.

The transportation time from demand zones to shelters are given in Table 18 in Appendix. For each earthquake scenario, the time (minute) between demand zones and shelters vary based on the road condition. Hence, we generate scenarios for the transportation time by multiplying nominal times, extracted from Mete and Zabinsky (2010), by different coefficients based on the magnitude and epicenter of the earthquake. Table 1 demonstrates how transportation times for AS, AC, HS, and HC scenarios are calculated. In addition, in this case study it is assumed that roads are available and in case of disruption in the network the time of transportation will increase so that the unavailable link cannot be used.

Table 1: Time of transportation from demand zones to shelters.

High impact		Average impact		Low impact	
Seattle	Cascadia	Seattle	Cascadia	Seattle	Cascadia
HS	HC	AS	AC	LS	LC
LS*(2)	LC*(2)	LS*(1.5)	LC*(1.5)	LS	LC

The transportation cost is considered as a function of the transportation time, road availability, and some other parameters over all earthquake scenarios as summarized in Table 19 in the Appendix. In this case study, the transportation cost is calculated by multiplying fuel cost and labour wages by transportation time. The salary of a driver who works during weekdays (7.5

hours a day) is considered around \$31/hour or ¢51.28 /minute. As for maintenance staff, a salary of ¢77 /minute is considered. Also, for the average fuel consumption cost, we multiply the average price of diesel ¢84.62/liter by 0.196 liter/minute (a standard for bus fuel consumption) resulting ¢16.57/minute. Therefore, the average transportation cost (human resources cost + fuel cost) is equal to ¢67.85/minute. Table 19 provides the cost of transportation in the Appendix. Finally, we assume that 46 people in average can be transported by each bus (transportation capacity).

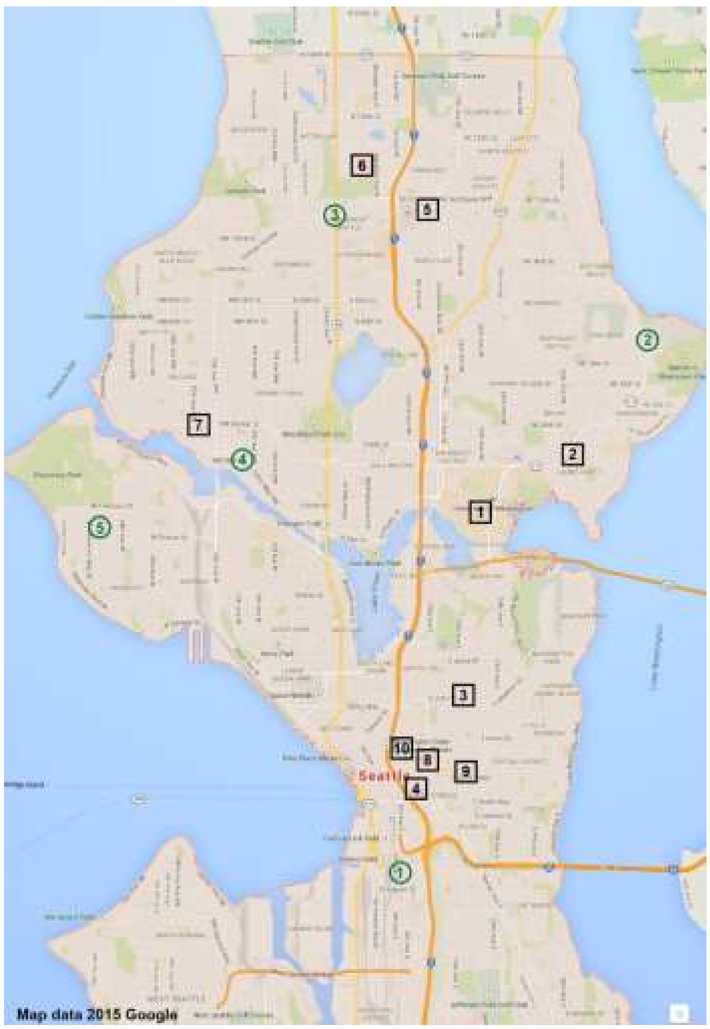

Figure 3: Seattle city, 10 demand zones and 5 shelter locations (adopted from Mete and Zabinsky (2010)*)*

5.2. Computational result

In this section, we present computational result for Shelter location/allocation models proposed in Chapter 4. In what follows, we first provide the results of the deterministic models; then we elaborate on the results of two-stage stochastic programming models. We also compare the solution of deterministic and stochastic models via calculating the expected value of perfect information (EVPI) and value of stochastic solution (VSS). Finally, we discuss the results of the proposed robust optimization model while varying the level of solution robustness.

5.2.1. Deterministic shelter location /allocation models

5.2.1.1. Model 1

Recall from Chapter 4 that model 1 decides on the optimal location of shelters and the best assignment of demand zones to each shelter. We solved model 1 for the 18 generated earthquake scenarios described in 5.1.1 and 5.1.2 and provide part of the results in Table 2. All related parameters (e.g., cost, capacity and availability of shelters, etc.) are provided in (Table 22)-(Table 25) in Appendix. It should be noted that in this model, we are assuming that some shelters are unavailable under certain scenarios. In addition, the optimal assignment of demand zones to shelters are summarized in Table 25 in Appendix.

Table 2: Optimal shelter locations in model 1

Shelter location / Scenario	1	2	3	4	5
1	X	X	X		X
2	X	X			X
3	X	X	X		
4	X			X	X
5	X				X
6	X			X	X
7	X	X			
8	X	X			
9	X				X
10	X				X
11	X				
12	X				X

13	X				
14					X
15					X
16					X
17					X
18					X

As we explained earlier, scenarios are sorted based on their impact from high to low from 1 to 18. Scenario one to six, seven to twelve, and thirteen to eighteen are categorised as high impact, average impact, and low impact scenarios, respectively. In higher impact scenarios from Table 2 we can observe that more shelters are needed to be opened in order to satisfy the demand. On the contrary, as expected, fewer shelters are required for low-impact earthquakes.

5.2.1.2. Model 2

Model 2 seeks the optimal location of shelters, the optimal number of population from different demand zones that must be transported to each shelter, and the number of population that could not be transported to shelters within 72h after earthquake while minimizing the cost of building shelters along with the transportation and the cost of leaving part of affected population in demand zones. In this model, a percentage of maximum capacity of shelters might be unavailable under certain scenarios. Table 3 summarizes the optimal location of shelters under different scenarios. Optimal assignment of demand zones to shelters are given in Table 29 in Appendix. As it can be observed in Table 4, for some scenarios, part of the demand is not satisfied due to insufficient capacity of shelters.

Table 3: Optimal shelter locations in model 2

Scenario \ Shelter location	1	2	3	4	5
1	X	X	X	X	X
2	X	X	X	X	X
3	X	X	X		X
4	X	X	X		X
5		X			X
6	X	X	X		X
7	X				X
8	X	X			
9	X				X

10	X	X			
11					X
12	X				X
13					X
14					X
15					X
16					X
17					X
18					X

Table 4: Number of population left at demand zones under each scenario

Scenarios	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
number of Population left at demand zones	1,450	862	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

5.2.2. Shelter location/allocation in HLNs under uncertainty

5.2.2.1. Modeling uncertainty

As we mentioned earlier in this chapter, 18 earthquake scenarios have been generated as summarized in Table 15 in the Appendix.

5.2.2.2. Two-stage stochastic models

The data description and computational results corresponding to the classical two-stage stochastic model, Model 1, and Model 2, described in Chapter 4, are provided as follows:

5.2.2.2.1. Classical Two-stage stochastic model

Recall from Chapter 4, the first stage decisions in this model is to find the optimal shelter locations while the second-stage decision is concerned with the assignment of demand zones to open shelters. Similar assumptions and data sets as in deterministic model 1 have been used to validate this model. By considering 18 earthquake scenarios, the objective function value of this model equals to \$33,314.58. In addition, in the first stage, 5 shelters are built in all candidate locations. The second stage decisions, i.e., the assignment of demand zones to shelters under different scenarios, are summarized in Table 30 in Appendix.

5.2.2.2.2. Two-stage stochastic model 1

As mentioned in Chapter 4, the difference between this model and the classical one is the possibility of opening new shelters after earthquake (at a higher cost) as another recourse (corrective) action in the presence of high impact earthquakes. The objective value of this model for this case study is \$11,467. The optimal shelter locations before and after earthquake are provided in Table 5 and Table 6.

Table 5: optimal shelter locations before earthquake

Shelters				
1	2	3	4	5
X				

Table 6: optimal shelter locations after earthquake

		Shelter				
		1	2	3	4	5
Scenarios	1		X	X		X
	2		X			X
	3		X	X		
	4				X	X
	5					X
	6				X	X
	7		X			
	8		X			
	9					X
	10					X
	11					
	12					X
	13					
	14					X
	15					
	16					
	17					
	18					

In comparison with the classical model, in model 1, less number of shelters are opened, resulting a lower objective function value. Nevertheless, Model 1 can decide on shelter installation in the second stage after occurrence of the earthquake.

The expected value of perfect information (EVPI) - model 1

According to the formula provided in Chapter 3, the expected value of perfect information (EVPI) for model 1 equals $1,827 as follows:

$$EVPI = RP - WS = 11{,}467 - 9658 = \mathbf{1{,}809} \tag{76}$$

This value can be interpreted as the maximum price the decision maker can pay in order to obtain full insight on the actual earthquake scenario.

The Value of the stochastic solution (VSS) - model 1

By considering scenario 12 as the average scenario (the one with the highest cumulative probability), we can calculate the mean-value solution through applying deterministic model 1 ((25)-(31)). After fixing the mean-value solution in two-stage model 1 ((46)-(54)), the expected objective function value, denoted as EEV is obtained ($12,483). Accordingly, the value of the stochastic solution (VSS) is calculated as follows:

$$VSS = EEV - RP = 12{,}483 - 11{,}467 = \mathbf{1{,}016} \tag{77}$$

As explained in Chapter 3, VSS compares the solution obtained by a deterministic model (under average scenario) with the one obtained from corresponding two-stage stochastic model.

5.2.2.2.3. Two-stage stochastic Model 2

In this model, the first-stage decision identifies the optimal location of shelters while the second-stage decisions incorporate the optimal location of shelters that must be opened after earthquake, the assignment of demand zones' population to shelters, and the number of population that could not be transported to shelters within 72h after earthquake under different scenarios. The objective function value of model 2 for this case study is $13,086. The optimal first and second-stage solutions are provided in Table 7 and Table 8. Number of population left at demand zones are also provided in Table 9. The rest of results for this model are provided in Table 32 and Table 33 in the Appendix.

Table 7: optimal shelter locations before earthquake

Shelters				
1	**2**	**3**	**4**	**5**
X				X

Table 8: optimal shelter locations after earthquake

		Shelter				
		1	**2**	**3**	**4**	**5**
Scenarios	**1**		X	X	X	
	2		X	X	X	
	3		X	X	X	
	4		X	X		
	5		X	X		
	6		X	X		
	7		X	X	X	
	8		X	X	X	
	9		X	X	X	
	10		X	X		
	11		X			
	12		X	X		
	13		X			
	14		X			
	15			X		
	16					
	17					
	18					

Table 9: Number of population left at demand zones under each scenario

Number of population left at each demand zone	Scenarios																	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
1	3,543	3,660	6,051	2,350	1,595	828	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	3,313	2,488	4,311	1,974	1,084	3,119	1,656	679	1,741	0	0	0	0	0	0	0	0	0
4	0	0	344	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	1,231	1,613	1,235	2,395	2,917	3,419	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	969	307	704	0	0	0	0	0	0	0	0	0	0	0	0
7	2,555	1,892	0	4,137	2,277	2,546	0	0	0	0	0	0	0	0	0	0	0	0
8	3,424	3,078	2,809	663	0	1,975	158	0	0	0	0	0	0	0	0	0	0	0
9	3,815	2,457	1,182	2,261	0	1,461	1,908	0	0	0	0	0	0	0	0	0	0	0
10	3,476	2,143	1,459	0	0	889	0	0	0	0	0	0	0	0	0	0	0	0
Total	**21,357**	**17,331**	**17,391**	**14,749**	**8,180**	**14,941**	**3,722**	**679**	**1,741**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

The expected value of perfect information (EVPI) - model 2

The expected value of perfect information for model 2 is calculated as follows:

$$EVPI = RP - WS = 13{,}086 - 11{,}259 = \mathbf{1,827} \tag{78}$$

The Value of the stochastic solution (VSS) - model 2

The value of the stochastic solution (VSS) for model 2 is calculated as follows:

$$VSS = EEV - RP = 15{,}935 - 13{,}087 = \mathbf{2,848} \tag{79}$$

Comparing the EVPI and VSS obtained from two-stage stochastic models 1 and 2, it can be observed that adopting two-stage stochastic model 2 instead of a deterministic mean-value model provides higher quality solutions comparing to model 1. This can be due to more flexible recourse actions included in model 2.

5.2.2.3. Robust optimization model (Conditional Value at Risk (CVaR))

Recall from Chapter 4, the difference between the robust optimization model with two-stage stochastic model 2 is introducing a robustness term in the objective function (CVaR). In other words, the objective function is to minimize the fixed cost of opening shelters, the expected cost of population transportation from demand zones to shelters, the expected cost of leaving part of affected population at demand zones along with minimizing the expected cost of leaving affected population (as a function of the number of population that cannot be transported to shelters within 72h after earthquake) under worst-case (extreme) earthquake scenarios at a certain confidence level. The objective function value of the robust optimization model by considering 80% confidence level ($\alpha = 0.8$) for this case study equals $574,468. The optimal first and second-stage decisions are provided in Table 10, Table 11, and Table 36 in the Appendix. The CVaR model is also solved for 90% and 95% confidence level for the same case study. The objective function values and optimal decisions can be found in Table 34 - Table 44 in Appendix.

Table 10: Optimal shelter locations before earthquake (α =0.8)

Shelters				
1	2	3	4	5
X				X

Table 11: Optimal shelter locations after earthquake (α =0.8)

		Shelter Locations After				
		1	**2**	**3**	**4**	**5**
Scenarios	1		X	X	X	
	2		X	X	X	
	3		X	X	X	
	4		X	X		
	5		X	X		
	6		X	X		
	7		X	X	X	
	8		X	X	X	
	9		X	X	X	
	10		X	X		
	11		X			
	12		X	X		
	13		X			
	14		X			
	15			X		
	16					
	17					
	18					

Table 12: Number of population left at demand zones under each scenario (α =0.8)

Number of population left at each demand zone	Scenarios																	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
1	3,543	3,660	6,051	2,350	1,595	1,717	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	3,313	2,488	4,311	1,974	1,084	3,119	1,656	679	1,741	0	0	0	0	0	0	0	0	0
4	0	0	344	110	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	1,231	2,325	1,235	2,395	2,917	3,419	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	969	307	704	0	0	0	0	0	0	0	0	0	0	0	0
7	2,555	1,180	0	4,137	2,277	2,546	0	0	0	0	0	0	0	0	0	0	0	0
8	4,895	3,078	2,809	553	0	1,975	158	0	0	0	0	0	0	0	0	0	0	0
9	3,815	2,457	1,182	2,261	0	1,461	1,908	0	0	0	0	0	0	0	0	0	0	0
10	2,005	2,143	1,459	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	**21,357**	**17,331**	**17,391**	**14,749**	**8,180**	**14,941**	**3,722**	**679**	**1,741**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 13 summarizes the objective function value, the expected cost, the cost of leaving affected population at demand zones at $(1-\alpha)\%$ worst-case earthquake scenarios $(\boldsymbol{\eta})$ and the expected cost of exceeding $\boldsymbol{\eta}$ for three different confidence levels (α), i.e., 80%, 90%, and 95% by considering $(\lambda = 1)$. As it can be observed in this table, by increasing the confidence level (α), the size of worst-case tail is increased. In other words, a higher expected worst-case cost $(\boldsymbol{\eta})$ is expected as we increase the confidence level. This result is also consistent with the definition of VaR and CVaR (see Figure 1) provided in Chapter 3. More results for different values of α are presented in Table 34-Table 44 in Appendix.

Table 13: Sensitivity analysis over CVaR parameters ($\lambda = 1$)

α	Two-Stage-Stochastic	0.8	0.9	0.95
η	-	87,050	186,100	747,050
Objective function	118,542	574,468	899,439	1,007,121
Expected cost	110,042	110,365	110,365	110,365
$\eta + \frac{1}{1-\alpha}\left[\sum_s p_r^s \phi^s\right]$	-	455,603	780,574	888,256

Comparing the results obtained for the robust shelter location/allocation model (CVaR) with the two-stage stochastic one, indicates that the configuration of the network (i.e., the location of shelters) in both models is the same. Nevertheless, the assignment of affected population to shelters, and consequently, the number of population left at demand zones are different. Table 14 and Figure 4 provide the number of population left under each scenario for CVaR and 2-stage-stochastic models. It can be clearly observed that this metric in two-stage-stochastic is greater than the CVaR, particularly in the high impact scenarios. Also, changing the confidence level in the robust model does not have any impact on the total number of left population in all demand zones. Nevertheless, by changing the confidence level the assignment of affected population to shelters and the number of left population vary among different demand zones.

Table 14: Number of population left under each scenario in CVaR and 2-Stage stochastic models

	2-Stage	**CVaR**		
		$\alpha = 0.8$	$\alpha = 0.9$	$\alpha = 0.95$
1	21,526	21,357	21,357	21,357
2	17,500	17,331	17,331	17,331
3	17,560	17,391	17,391	17,391
4	14,749	14,749	14,749	14,749
5	8,180	8,180	8,180	8,180
6	14,941	14,941	14,941	14,941
7	3,722	3,722	3,722	3,722
8	679	679	679	679
9	1,741	1,741	1,741	1,741
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	0	0	0	0
18	0	0	0	0

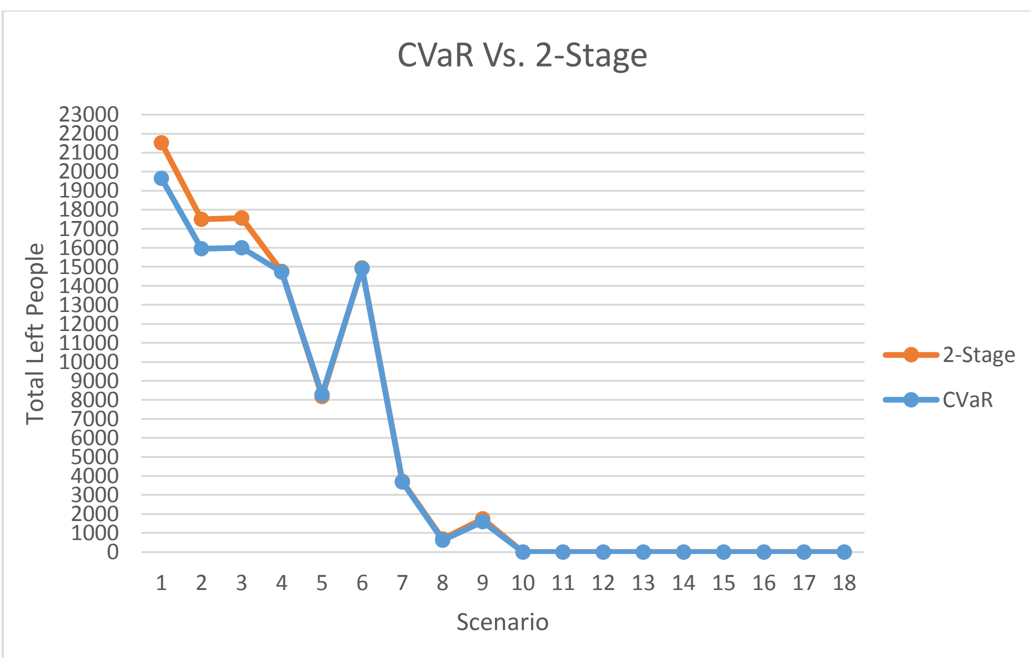

Figure 4: Comparing the number of left population in CVaR and 2-stage-stochastic models

Chapter 6: Conclusion and future research

In this thesis, we investigated shelter location/allocation problem that can be classified as a preparedness planning tool in emergency logistics. By restricting our attention to earthquakes, in this problem we are looking for the selection of safe areas to build temporary shelters as well as allocation of affected population located in demand zones (e.g., areas close to faults) to those shelters. Two variants of this problem were first formulated in a deterministic context that differ in terms of the way population in various demand zones can be allocated to shelters. Next, by focusing on the most flexible deterministic model, in order to incorporate the uncertain nature of earthquakes in terms of epicenter and magnitude, this model was reformulated by the aid of two stochastic programming and robust optimization approaches. More precisely, we proposed two types of stochastic shelter location/allocation models with different recourse (corrective) actions in the presence of various earthquake scenarios. While the classical model decides on shelter locations without any information on earthquake scenario, the second one provides the possibility of opening extra shelters once the earthquake scenario is revealed.

Although two-stage stochastic models protect the aforementioned disaster preparedness plan against different earthquake scenarios, the plan proposed by these models is expected to perform well in the mean sense. Nonetheless, the plan is not protected against certain worst-case scenarios (i.e., a devastating earthquake during rush hour in a big city) in terms of the number of population that cannot be transported to shelters in a timely manner. In order to avoid the increased number of casualties as a consequence of such extreme scenarios, we introduced a risk measure (Conditional-Value-at-Risk) to the objective function of two-stage stochastic model. The objective of this robust model is to minimize the cost of casualties under a given percentage of worst-case scenarios. Finally, the proposed deterministic, stochastic and robust optimization models were tested via a realistic case study. The latter was carefully designed based on the real data in the existing literature.

The value of stochastic solution calculated in this case study clearly revealed the importance of formulating the shelter location/allocation problem by stochastic programming approach. Further, it was observed providing the possibility of opening shelters after earthquake (i.e., under high impact scenarios) would significantly reduce the fixed investment required to open shelters comparing to the case where opening shelters is considered as a first-stage decision that cannot be modified once the actual scenario is revealed to the decision-maker. Finally, the plan proposed by the robust optimization model is different from the stochastic one in terms of opening more shelters under high-impact scenarios. The reason is to protect the plan (i.e., minimizing the expected number of casualties) under worst-case scenarios at a given confidence level.

Although the above-mentioned models were applied for earthquake emergency logistics, they are also applicable to other natural disasters. This study can be extended into future avenues of research as follows:

- The data set can be improved so as to include more earthquake scenarios in terms of epicenter and magnitude. Also, a larger geographic area including more faults, demand zones, and candidate safe locations for opening shelters could be investigated. This, however, would increase the size of stochastic and robust optimization models and make them hard to solve by commercial solvers. Hence, efficient solution algorithms such as decomposition methods should be developed to solve the above-mentioned models.
- The proposed stochastic and robust shelter location/allocation models could be better validated through developing a simulation platform that mimics the behavior of earthquakes in terms of epicenter and magnitude. In contrast, this calls for reliable historical earthquake data along with sophisticated time-series analysis approaches in order to realistically model the behavior of such phenomena that are also sporadic in nature.
- The preparedness planning models proposed in this thesis could be integrated with response models such as the post-disaster vehicle routing problem. The idea is to better align population allocation decisions in current problem with the type and capacity of available fleet of vehicles along with their routing considering a transportation network partially impaired by an earthquake.

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Appendix

8.1. Data

Table 15: Likelihoods of scenarios

High impact						Average impact						Low impact					
Seattle			Cascadia			Seattle			Cascadia			Seattle			Cascadia		
HS			HC			AS			AC			LS			LC		
W	R	N	W	R	N	W	R	N	W	R	N	W	R	N	W	R	N
0.01	**0.01**	**0.02**	**0.02**	**0.01**	**0.03**	**0.04**	**0.03**	**0.09**	**0.07**	**0.04**	**0.13**	**0.06**	**0.04**	**0.11**	**0.08**	**0.05**	**0.17**

Table 16: Demand scenarios

High impact		Average impact		Low impact	
Seattle	Cascadia	Seattle	Cascadia	Seattle	Cascadia
HS	HC	AS	AC	LS	LC
AS*2	HC	AS	HC/2	AS/2	HC/4

Table 17: Demand (population) in need of transportation

Demand zones	High impact						Average impact						Low impact					
	Seattle			Cascadia			Seattle			Cascadia			Seattle			Cascadia		
	W	R	N	W	R	N	W	R	N	W	R	N	W	R	N	W	R	N
1	4209	4028	6327	3078	2769	4541	2104	2014	3164	1539	1384	2271	1052	1007	1582	770	692	1135
2	2273	2571	2663	1765	1319	2383	1136	1286	1331	883	660	1192	568	643	666	441	330	596
3	3313	2488	4311	1974	1716	3119	1656	1244	2155	987	858	1560	828	622	1078	494	429	780
4	1021	2303	2836	1807	2371	2502	511	1151	1418	904	1186	1251	255	576	709	452	593	626
5	1529	2325	3224	2395	2917	3419	764	1162	1612	1198	1458	1710	382	581	806	599	729	855
6	2086	1672	1942	1267	605	704	1043	836	971	634	302	352	522	418	486	317	151	176
7	6681	3955	2579	4137	2277	2546	3340	1977	1290	2068	1138	1273	1670	989	645	1034	569	637
8	4895	3078	2809	3045	1268	1975	2447	1539	1404	1522	634	987	1224	770	702	761	317	494
9	3815	2457	1182	2261	1345	1461	1908	1229	591	1131	673	730	954	614	296	565	336	365
10	3476	2332	1459	2016	1002	1287	1738	1166	730	1008	501	644	869	583	365	504	251	322

Table 18: Duration of transportation time between shelter locations and demand zones

Demand zones	**Shelters**	**High impact**						**Average impact**						**Low impact**					
		Seattle			Cascadia			Seattle			Cascadia			Seattle			Cascadia		
		W	R	N	W	R	N	W	R	N	W	R	N	W	R	N	W	R	N
1	**1**	51	140	29	29	60	7	39	105	22	22	45	6	26	70	15	15	30	4
1	**2**	17	17	7	26	26	17	13	13	6	20	20	13	8	8	4	13	13	8
1	**3**	65	163	37	37	70	9	49	123	28	28	53	7	33	82	19	19	35	5
1	**4**	16	16	8	24	24	16	12	12	6	18	18	12	8	8	4	12	12	8
1	**5**	98	140	56	56	60	14	74	105	42	42	45	11	49	70	28	28	30	7
2	**1**	70	140	40	40	60	10	53	105	30	30	45	8	35	70	20	20	30	5
2	**2**	9	9	5	14	14	9	7	7	4	11	11	7	5	5	2	7	7	5
2	**3**	75	117	43	43	50	11	56	88	32	32	38	8	37	58	21	21	25	5
2	**4**	23	33	11	34	50	23	17	25	9	26	38	17	11	17	6	17	25	11
2	**5**	37	37	19	56	56	37	28	28	14	42	42	28	19	19	9	28	28	19
3	**1**	18	18	12	12	12	6	14	14	9	9	9	5	9	9	6	6	6	3
3	**2**	89	89	51	51	38	13	67	67	38	38	29	10	44	44	25	25	19	6
3	**3**	75	163	43	43	70	11	56	123	32	32	53	8	37	82	21	21	35	5
3	**4**	79	79	45	45	34	11	60	60	34	34	26	9	40	40	23	23	17	6
3	**5**	103	103	59	59	44	15	77	77	44	44	33	11	51	51	29	29	22	7
4	**1**	10	10	7	7	7	3	8	8	5	5	5	3	5	5	3	3	3	2
4	**2**	84	163	48	48	70	12	63	123	36	36	53	9	42	82	24	24	35	6
4	**3**	65	163	37	37	70	9	49	123	28	28	53	7	33	82	19	19	35	5
4	**4**	79	79	45	45	34	11	60	60	34	34	26	9	40	40	23	23	17	6
4	**5**	44	44	29	29	29	15	33	33	22	22	22	11	22	22	15	15	15	7
5	**1**	70	140	40	40	60	10	53	105	30	30	45	8	35	70	20	20	30	5
5	**2**	17	17	9	26	26	17	13	13	7	20	20	13	9	9	4	13	13	9
5	**3**	9	9	5	14	14	9	7	7	4	11	11	7	5	5	2	7	7	5
5	**4**	23	23	11	34	34	23	17	17	9	26	26	17	11	11	6	17	17	11
5	**5**	72	53	18	126	126	72	54	40	14	95	95	54	36	27	9	63	63	36
6	**1**	75	140	43	43	60	11	56	105	32	32	45	8	37	70	21	21	30	5
6	**2**	21	33	11	32	50	21	16	25	8	24	38	16	11	17	5	16	25	11
6	**3**	5	5	3	8	8	5	4	4	2	6	6	4	3	3	1	4	4	3
6	**4**	20	33	10	30	50	20	15	25	8	23	38	15	10	17	5	15	25	10
6	**5**	64	48	16	112	112	64	48	36	12	84	84	48	32	24	8	56	56	32
7	**1**	98	163	56	56	70	14	74	123	42	42	53	11	49	82	28	28	35	7
7	**2**	28	40	14	42	60	28	21	30	11	32	45	21	14	20	7	21	30	14
7	**3**	16	9	8	24	24	16	12	7	6	18	18	12	8	5	4	12	12	8

7	**4**	27	47	13	40	70	27	20	35	10	30	53	20	13	23	7	20	35	13
7	**5**	32	24	8	56	56	32	24	18	6	42	42	24	16	12	4	28	28	16
8	**1**	12	12	8	8	8	4	9	9	6	6	6	3	6	6	4	4	4	2
8	**2**	89	163	51	51	70	13	67	123	38	38	53	10	44	82	25	25	35	6
8	**3**	30	70	20	20	47	10	23	53	15	15	35	8	15	35	10	10	23	5
8	**4**	36	60	24	24	40	12	27	45	18	18	30	9	18	30	12	12	20	6
8	**5**	46	46	31	31	31	15	35	35	23	23	23	12	23	23	15	15	15	8
9	**1**	16	16	11	11	11	5	12	12	8	8	8	4	8	8	5	5	5	3
9	**2**	93	163	53	53	70	13	70	123	40	40	53	10	47	82	27	27	35	7
9	**3**	34	70	23	23	47	11	26	53	17	17	35	9	17	35	11	11	23	6
9	**4**	38	70	25	25	47	13	29	53	19	19	35	10	19	35	13	13	23	6
9	**5**	50	50	33	33	33	17	38	38	25	25	25	13	25	25	17	17	17	8
10	**1**	12	12	8	8	8	4	9	9	6	6	6	3	6	6	4	4	4	2
10	**2**	79	163	45	45	70	11	60	123	34	34	53	9	40	82	23	23	35	6
10	**3**	10	10	7	7	47	3	8	8	5	5	35	3	5	5	3	3	23	2
10	**4**	34	34	23	23	23	11	26	26	17	17	17	9	17	17	11	11	11	6
10	**5**	42	60	28	28	40	14	32	45	21	21	30	11	21	30	14	14	20	7

Table 19: Cost of transportation from shelter locations to demand zones

Demand zones	**Shelters**	**High impact**						**Average impact**						**Low impact**					
		Seattle			**Cascadia**			**Seattle**			**Cascadia**			**Seattle**			**Cascadia**		
		W	**R**	**N**	**W**	**R**	**N**	**W**	**R**	**N**	**W**	**R**	**N**	**W**	**R**	**N**	**W**	**R**	**N**
1	**1**	35	95	20	20	41	5	26	71	15	15	31	4	17	47	10	10	20	2
1	**2**	11	11	5	18	18	11	8	8	4	13	13	8	6	6	2	9	9	6
1	**3**	44	111	25	25	47	6	33	83	19	19	36	5	22	55	13	13	24	3
1	**4**	11	11	5	16	16	11	8	8	4	12	12	8	5	5	3	8	8	5
1	**5**	66	95	38	38	41	9	50	71	28	28	31	7	33	47	19	19	20	5
2	**1**	47	95	27	27	41	7	36	71	20	20	31	5	24	47	14	14	20	3
2	**2**	6	6	3	9	9	6	5	5	2	7	7	5	3	3	2	5	5	3
2	**3**	51	79	29	29	34	7	38	59	22	22	25	5	25	40	14	14	17	4
2	**4**	15	23	8	23	34	15	12	17	6	17	25	12	8	11	4	12	17	8
2	**5**	25	25	13	38	38	25	19	19	9	28	28	19	13	13	6	19	19	13
3	**1**	12	12	8	8	8	4	9	9	6	6	6	3	6	6	4	4	4	2
3	**2**	60	60	34	34	26	9	45	45	26	26	19	6	30	30	17	17	13	4
3	**3**	51	111	29	29	47	7	38	83	22	22	36	5	25	55	14	14	24	4
3	**4**	54	54	31	31	23	8	40	40	23	23	17	6	27	27	15	15	12	4

3	**5**	70	70	40	40	30	10	52	52	30	30	22	7	35	35	20	20	15	5
4	**1**	7	7	5	5	5	2	5	5	3	3	3	2	3	3	2	2	2	1
4	**2**	57	111	33	33	47	8	43	83	24	24	36	6	28	55	16	16	24	4
4	**3**	44	111	25	25	47	6	33	83	19	19	36	5	22	55	13	13	24	3
4	**4**	54	54	31	31	23	8	40	40	23	23	17	6	27	27	15	15	12	4
4	**5**	30	30	20	20	20	10	22	22	15	15	15	7	15	15	10	10	10	5
5	**1**	47	95	27	27	41	7	36	71	20	20	31	5	24	47	14	14	20	3
5	**2**	12	12	6	18	18	12	9	9	4	13	13	9	6	6	3	9	9	6
5	**3**	6	6	3	9	9	6	5	5	2	7	7	5	3	3	2	5	5	3
5	**4**	15	15	8	23	23	15	12	12	6	17	17	12	8	8	4	12	12	8
5	**5**	49	36	12	85	85	49	37	27	9	64	64	37	24	18	6	43	43	24
6	**1**	51	95	29	29	41	7	38	71	22	22	31	5	25	47	14	14	20	4
6	**2**	14	23	7	22	34	14	11	17	5	16	25	11	7	11	4	11	17	7
6	**3**	4	4	2	5	5	4	3	3	1	4	4	3	2	2	1	3	3	2
6	**4**	14	23	7	20	34	14	10	17	5	15	25	10	7	11	3	10	17	7
6	**5**	43	33	11	76	76	43	33	24	8	57	57	33	22	16	5	38	38	22
7	**1**	66	111	38	38	47	9	50	83	28	28	36	7	33	55	19	19	24	5
7	**2**	19	27	9	28	41	19	14	20	7	21	31	14	9	14	5	14	20	9
7	**3**	11	6	5	16	16	11	8	5	4	12	12	8	5	3	3	8	8	5
7	**4**	18	32	9	27	47	18	14	24	7	20	36	14	9	16	5	14	24	9
7	**5**	22	16	5	38	38	22	16	12	4	28	28	16	11	8	3	19	19	11
8	**1**	8	8	5	5	5	3	6	6	4	4	4	2	4	4	3	3	3	1
8	**2**	60	111	34	34	47	9	45	83	26	26	36	6	30	55	17	17	24	4
8	**3**	20	47	14	14	32	7	15	36	10	10	24	5	10	24	7	7	16	3
8	**4**	24	41	16	16	27	8	18	31	12	12	20	6	12	20	8	8	14	4
8	**5**	31	31	21	21	21	10	23	23	16	16	16	8	16	16	10	10	10	5
9	**1**	11	11	7	7	7	4	8	8	5	5	5	3	5	5	4	4	4	2
9	**2**	63	111	36	36	47	9	47	83	27	27	36	7	32	55	18	18	24	5
9	**3**	23	47	15	15	32	8	17	36	12	12	24	6	12	24	8	8	16	4
9	**4**	26	47	17	17	32	9	19	36	13	13	24	6	13	24	9	9	16	4
9	**5**	34	34	23	23	23	11	25	25	17	17	17	8	17	17	11	11	11	6
10	**1**	8	8	5	5	5	3	6	6	4	4	4	2	4	4	3	3	3	1
10	**2**	54	111	31	31	47	8	40	83	23	23	36	6	27	55	15	15	24	4
10	**3**	7	7	5	5	32	2	5	5	3	3	24	2	3	3	2	2	16	1
10	**4**	23	23	15	15	15	8	17	17	12	12	12	6	12	12	8	8	8	4
10	**5**	28	41	19	19	27	9	21	31	14	14	20	7	14	20	9	9	14	5

Table 20: Monthly average cost of Diesel 2014-15

Year	2014												2015					Average
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	
Price	100.3	103.6	97.9	94.5	90.4	88.3	85.4	85.7	82.9	79	81.8	75.6	70.2	79.3	79.6	71.7	72.3	**¢84.62**

Table 21: Cost of building shelters

Shelter locations	Fixed cost for preparedness	Fixed cost after the earthquake
1	5000	7500
2	4850	7275
3	7500	11250
4	11000	16500
5	3500	5250

8.2. Deterministic shelter location /allocation in HLNs

8.2.1. Model 1

8.2.1.1. Data

Table 22: Capacity of shelter locations (person)

		Shelters					
		1	2	3	4	5	Total
Scenarios	1	10000	10000	10000	6000	8000	44000
	2	10000	10000	10000	6000	8000	44000
	3	10000	10000	10000	6000	8000	44000
	4	10000	10000	10000	6000	8000	44000
	5	10000	10000	10000	6000	8000	44000
	6	10000	10000	10000	6000	8000	44000
	7	10000	10000	10000	6000	8000	44000
	8	10000	10000	10000	6000	8000	44000
	9	10000	10000	10000	6000	8000	44000
	10	10000	10000	10000	6000	8000	44000
	11	10000	10000	10000	6000	8000	44000
	12	10000	10000	10000	6000	8000	44000
	13	10000	10000	10000	6000	8000	44000
	14	10000	10000	10000	6000	8000	44000
	15	10000	10000	10000	6000	8000	44000
	16	10000	10000	10000	6000	8000	44000
	17	10000	10000	10000	6000	8000	44000
	18	10000	10000	10000	6000	8000	44000

Table 23: Availability of shelter locations

		Shelters				
		1	2	3	4	5
Scenarios	1	1	1	1	1	1
	2	1	1	1	1	1
	3	1	1	1	1	1
	4	1	0	0	1	1
	5	1	0	0	1	1
	6	1	0	0	1	1
	7	1	1	1	1	1
	8	1	1	1	1	1
	9	1	1	1	1	1
	10	1	1	1	1	1
	11	1	1	1	1	1
	12	1	1	1	1	1
	13	1	1	1	1	1
	14	0	1	1	1	1
	15	1	0	1	1	1
	16	1	1	1	1	1
	17	1	1	1	1	1
	18	1	1	1	1	1

8.2.1.2. Result

Table 24: Objective values of model 1 for all earthquake scenarios

Scenarios	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Objective Value	31,137	24,754	22,409	30,640	18,526	24,212	13,012	12,671	11,012	11,999	8,815	9,668	7,777	6,665	5,358	5,961	5,473	4,764

Table 25: Assigned demand zones to shelters

		Shelter location																								
		1	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
		1					**5**					**9**					**13**					**17**				
Demand zone	**1**	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1
	2	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1
	3	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1
	4	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1
	5	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1
	6	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1
	7	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1
	8	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1
	9	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1
	10	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1
		2					**6**					**10**					**14**					**18**				
	1	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1
	2	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1
	3	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1
	4	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1
	5	0	0	0	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1
	6	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1
	7	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1
	8	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1
	9	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1
	10	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1
		3					**7**					**11**					**15**									
	1	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1					
	2	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1					
	3	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1					
	4	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1					
	5	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1					
	6	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1					
	7	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1					
	8	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1					
	9	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1					
	10	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1					
		4					**8**					**12**					**16**									
	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1					

	2	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1
	3	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1
	4	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1
	5	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1
	6	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1
	7	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1
	8	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1
	9	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1
	10	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1

8.2.2. Model 2

8.2.2.1. Data

Table 26: Capacity of shelter locations (person)

		Shelters					
		1	**2**	**3**	**4**	**5**	Total
Scenarios	**1**	6998	7387	7949	2261	11002	35597
	2	6998	7387	7949	2261	11002	35597
	3	6998	7387	7949	2261	11002	35597
	4	6998	7387	7949	2261	11002	35597
	5	6998	7387	7949	2261	11002	35597
	6	6998	7387	7949	2261	11002	35597
	7	6998	7387	7949	2261	11002	35597
	8	6998	7387	7949	2261	11002	35597
	9	6998	7387	7949	2261	11002	35597
	10	6998	7387	7949	2261	11002	35597
	11	6998	7387	7949	2261	11002	35597
	12	6998	7387	7949	2261	11002	35597
	13	6998	7387	7949	2261	11002	35597
	14	6998	7387	7949	2261	11002	35597
	15	6998	7387	7949	2261	11002	35597
	16	6998	7387	7949	2261	11002	35597
	17	6998	7387	7949	2261	11002	35597
	18	6998	7387	7949	2261	11002	35597

Table 27: Availability of shelter locations

		Shelters				
		1	**2**	**3**	**4**	**5**
Scenarios	**1**	0.95	1	0.8	0.2	1
	2	0.95	1	0.8	0.2	0.5
	3	0.95	1	0.8	0.2	1
	4	0.95	0.9	0.1	0	0.9
	5	0.95	0.9	0.1	0	1
	6	0.95	0.9	0.1	0	0.9
	7	1	1	1	0.5	1
	8	1	1	1	0.5	1
	9	1	1	1	0.5	1
	10	1	1	1	0.5	1
	11	1	1	1	0.5	1
	12	1	1	1	0.5	1
	13	1	1	1	1	1
	14	0	1	1	1	1
	15	1	0	1	1	1
	16	1	1	1	1	1
	17	1	1	1	1	1
	18	1	1	1	1	1

8.2.2.2. Result

Table 28: Objective values of model 2 for all earthquake scenarios

Scenarios	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Objective Value	114,653.478	81,618.870	25,888.804	30,441.891	17,631.696	25,021.978	15,108.565	12,670.978	11,623.000	12,453.109	9,414.022	9,927.326	7,019.457	6,664.652	5,357.957	5,961.283	5,472.848	4,763.522

Table 29: Transported people to shelters

	Shelter location																								
Demand zone	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	1					**5**					**9**					**13**					**17**				
1	0	3911	0	298	0	0	1807	0	0	962	3164	0	0	0	0	0	0	0	0	1052	0	0	0	0	692
2	0	2273	0	0	0	0	1319	0	0	0	0	0	0	0	1331	0	0	0	0	568	0	0	0	0	330
3	1863	0	0	0	0	0	0	0	0	1716	2155	0	0	0	0	0	0	0	0	828	0	0	0	0	429
4	0	0	0	0	1021	0	0	0	0	2371	0	0	0	0	1418	0	0	0	0	255	0	0	0	0	593
5	0	1203	326	0	0	0	2917	0	0	0	0	0	0	0	1612	0	0	0	0	382	0	0	0	0	729
6	0	0	2086	0	0	0	605	0	0	0	0	0	0	0	971	0	0	0	0	522	0	0	0	0	151
7	0	0	471	0	6210	0	0	0	0	2277	0	0	0	0	1290	0	0	0	0	1670	0	0	0	0	569
8	4785	0	0	0	110	0	0	0	0	1268	1088	0	0	0	316	0	0	0	0	1224	0	0	0	0	317
9	0	0	0	154	3661	0	0	0	0	1345	591	0	0	0	0	0	0	0	0	954	0	0	0	0	336
10	0	0	3476	0	0	0	0	0	0	1002	0	0	0	0	730	0	0	0	0	869	0	0	0	0	251
	2					**6**					**10**					**14**					**18**				
1	0	3576	0	452	0	0	0	0	0	4541	0	1539	0	0	0	0	0	0	0	1007	0	0	0	0	1135
2	0	2571	0	0	0	0	2383	0	0	0	0	883	0	0	0	0	0	0	0	643	0	0	0	0	596
3	1626	0	0	0	0	0	0	0	0	3119	987	0	0	0	0	0	0	0	0	622	0	0	0	0	780
4	1944	0	0	0	359	2502	0	0	0	0	904	0	0	0	0	0	0	0	0	576	0	0	0	0	626
5	0	1240	1085	0	0	0	3329	90	0	0	0	1198	0	0	0	0	0	0	0	581	0	0	0	0	855
6	0	0	1672	0	0	0	0	704	0	0	0	634	0	0	0	0	0	0	0	418	0	0	0	0	176
7	0	0	1270	0	2685	2546	0	0	0	0	0	2068	0	0	0	0	0	0	0	989	0	0	0	0	637
8	3078	0	0	0	0	1600	0	0	0	375	1522	0	0	0	0	0	0	0	0	770	0	0	0	0	494
9	0	0	0	0	2457	0	936	0	0	525	1131	0	0	0	0	0	0	0	0	614	0	0	0	0	365
10	0	0	2332	0	0	0	0	0	0	1287	1008	0	0	0	0	0	0	0	0	583	0	0	0	0	322
	3					**7**					**11**					**15**									
1	0	6327	0	0	0	2104	0	0	0	0	0	0	0	0	1384	0	0	0	0	1582					
2	0	1060	0	0	1603	0	0	0	0	1136	0	0	0	0	660	0	0	0	0	666					
3	4311	0	0	0	0	1656	0	0	0	0	0	0	0	0	858	0	0	0	0	1078					
4	0	0	0	0	2836	0	0	0	0	511	0	0	0	0	1186	0	0	0	0	709					
5	0	0	3224	0	0	0	0	0	0	764	0	0	0	0	1458	0	0	0	0	806					
6	0	0	1676	0	266	0	0	0	0	1043	0	0	0	0	302	0	0	0	0	486					
7	0	0	0	0	2579	0	0	0	0	3340	0	0	0	0	1138	0	0	0	0	645					
8	1155	0	0	0	1654	1330	0	0	0	1117	0	0	0	0	634	0	0	0	0	702					
9	1182	0	0	0	0	1908	0	0	0	0	0	0	0	0	673	0	0	0	0	296					
10	0	0	1459	0	0	0	0	0	0	1738	0	0	0	0	501	0	0	0	0	365					
	4					**8**					**12**					**16**									

	1	1652	1426	0	0	0	0	2014	0	0	0	0	0	0	0	2271	0	0	0	0	770
	2	0	1765	0	0	0	0	1286	0	0	0	1192	0	0	0	0	0	0	0	0	441
	3	1974	0	0	0	0	1244	0	0	0	0	0	0	0	0	1560	0	0	0	0	494
	4	0	0	0	0	1807	1151	0	0	0	0	110	0	0	0	1141	0	0	0	0	452
	5	0	2395	0	0	0	0	1162	0	0	0	1710	0	0	0	0	0	0	0	0	599
	6	0	473	794	0	0	0	836	0	0	0	352	0	0	0	0	0	0	0	0	317
	7	0	589	0	0	3548	0	1977	0	0	0	1273	0	0	0	0	0	0	0	0	1034
	8	3022	0	0	0	23	1539	0	0	0	0	987	0	0	0	0	0	0	0	0	761
	9	0	0	0	0	2261	1229	0	0	0	0	730	0	0	0	0	0	0	0	0	565
	10	0	0	0	0	2016	1166	0	0	0	0	644	0	0	0	0	0	0	0	0	504

8.3. Shelter location/allocation in HLNs Under uncertainty

8.3.1. Two-stage stochastic models

8.3.1.1. Classical two-stage stochastic model

8.3.1.1.1. Data

In this model, Capacity and Shelter availability are considered the same as model 1.

8.3.1.1.2. Result

The objective values is 33,314.

Table 30: Assigned demand zones to shelters

		Shelter location																								
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
		1					**5**					**9**					**13**					**17**				
Demand zone	1	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0
	2	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0
	3	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
	4	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
	5	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
	6	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
	7	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0
	8	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
	9	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
	10	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0
		2					**6**					**10**					**14**					**18**				
	1	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	1	0	0	0	0
	2	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0
	3	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0
	4	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0
	5	0	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0
	6	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
	7	0	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0
	8	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0
	9	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0
	10	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0
		3					**7**					**11**					**15**									
	1	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0					
	2	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0					
	3	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0					
	4	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0					
	5	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0					
	6	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0					
	7	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0					
	8	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0					
	9	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0					
	10	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0					
		4					**8**					**12**					**16**									

1	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0	0	0	1	0
2	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0
3	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
4	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
5	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
6	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
7	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0
8	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
9	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
10	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0

8.3.1.2. Model 1

8.3.1.2.1. Data

In this model, Capacity and Shelter availability are considered the same as model 1.

8.3.1.2.2. Result

The objective values is 11,467.

Table 31: Assigned demand zones to shelters

	Shelter location																								
	1	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
Demand zone	**1**					**5**					**9**					**13**					**17**				
1	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
2	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0
3	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
4	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
5	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0
6	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0
7	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0
8	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
9	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
10	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
	2					**6**					**10**					**14**					**18**				
1	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0

2	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0
3	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0
4	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0
5	0	0	0	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0
6	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0
7	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0
8	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0
9	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0
10	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0

	3					**7**					**11**					**15**				
1	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0
2	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0
3	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
4	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
5	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0
6	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0
7	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0
8	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
9	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
10	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0

	4					**8**					**12**					**16**				
1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0
2	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0
3	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
4	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
5	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0
6	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0
7	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0
8	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
9	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
10	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0

8.3.1.3. Model 2

8.3.1.3.1. Data

Table 32: Capacity of shelter locations (person)

		Shelters					
		1	2	3	4	5	Total
Scenarios	1	2624	2770	2981	848	4126	13349
	2	2624	2770	2981	848	4126	13349
	3	2624	2770	2981	848	4126	13349
	4	2624	2770	2981	848	4126	13349
	5	2624	2770	2981	848	4126	13349
	6	2624	2770	2981	848	4126	13349
	7	2624	2770	2981	848	4126	13349
	8	2624	2770	2981	848	4126	13349
	9	2624	2770	2981	848	4126	13349
	10	2624	2770	2981	848	4126	13349
	11	2624	2770	2981	848	4126	13349
	12	2624	2770	2981	848	4126	13349
	13	2624	2770	2981	848	4126	13349
	14	2624	2770	2981	848	4126	13349
	15	2624	2770	2981	848	4126	13349
	16	2624	2770	2981	848	4126	13349
	17	2624	2770	2981	848	4126	13349
	18	2624	2770	2981	848	4126	13349

The availability of shelter locations are considered the same in all kinds of model 2.

8.3.1.3.2. Result

Table 33: Transported people to shelters

Demand zone	Shelter location																								
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	1					5					9					13					17				
1	0	497	0	169	0	0	1174	0	0	0	0	2740	0	424	0	0	1052	0	0	0	0	0	0	0	692
2	0	2273	0	0	0	0	1319	0	0	0	0	30	0	0	1301	0	568	0	0	0	0	0	0	0	330
3	0	0	0	0	0	632	0	0	0	0	414	0	0	0	0	828	0	0	0	0	429	0	0	0	0
4	1021	0	0	0	0	0	0	0	0	2371	1418	0	0	0	0	255	0	0	0	0	593	0	0	0	0
5	0	0	298	0	0	0	0	0	0	0	0	0	1612	0	0	0	382	0	0	0	729	0	0	0	0
6	0	0	2086	0	0	0	0	298	0	0	0	0	639	0	332	0	522	0	0	0	151	0	0	0	0
7	0	0	0	0	4126	0	0	0	0	0	0	0	0	0	1290	0	246	0	0	1424	0	0	0	0	569
8	1471	0	0	0	0	0	0	0	0	1268	201	0	0	0	1203	1224	0	0	0	0	317	0	0	0	0
9	0	0	0	0	0	858	0	0	0	487	591	0	0	0	0	317	0	0	0	637	154	0	0	0	182
10	0	0	0	0	0	1002	0	0	0	0	0	0	730	0	0	0	0	0	0	869	251	0	0	0	0

Demand zone	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	2					6					10					14					18				
1	0	199	0	169	0	0	0	0	0	3713	0	1539	0	0	0	0	1007	0	0	0	0	0	0	0	1135
2	0	2571	0	0	0	0	2383	0	0	0	0	883	0	0	0	0	643	0	0	0	596	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	987	0	0	0	0	0	121	0	0	501	0	0	0	0	780
4	2303	0	0	0	0	2492	10	0	0	0	904	0	0	0	0	0	0	0	0	576	0	0	0	0	626
5	0	0	712	0	0	0	0	0	0	0	0	348	850	0	0	0	581	0	0	0	855	0	0	0	0
6	0	0	1672	0	0	0	0	0	0	0	0	0	634	0	0	0	418	0	0	0	176	0	0	0	0
7	0	0	0	0	2063	0	0	0	0	0	0	0	1497	0	571	0	0	0	0	989	637	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1522	0	0	0	0	770	360	0	0	0	134
9	0	0	0	0	0	0	0	0	0	0	733	0	0	0	398	0	0	0	0	614	0	0	0	0	365
10	189	0	0	0	0	0	100	298	0	0	0	0	0	0	1008	0	0	0	0	583	0	0	0	0	322

Demand zone	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	3					7					11					15				
1	0	107	0	169	0	0	1680	0	424	0	0	652	0	0	732	135	0	1447	0	0
2	0	2663	0	0	0	0	1090	0	0	46	0	660	0	0	0	0	0	0	0	666
3	0	0	0	0	0	0	0	0	0	0	858	0	0	0	0	1078	0	0	0	0
4	2492	0	0	0	0	335	0	0	0	176	963	0	0	0	223	709	0	0	0	0
5	0	0	1989	0	0	0	0	764	0	0	0	1458	0	0	0	0	0	683	0	123
6	0	0	395	0	1547	0	0	1043	0	0	302	0	0	0	0	0	0	486	0	0
7	0	0	0	0	2579	0	0	0	0	3340	0	0	0	0	1138	0	0	0	0	645
8	0	0	0	0	0	2289	0	0	0	0	0	0	0	0	634	702	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	673	0	0	0	0	296
10	0	0	0	0	0	0	0	1174	0	564	501	0	0	0	0	0	0	365	0	0

	4					8					12					16				
1	0	728	0	0	0	0	1590	0	424	0	0	0	0	0	2271	770	0	0	0	0
2	0	1765	0	0	0	0	997	0	0	289	0	1192	0	0	0	0	0	0	0	441
3	0	0	0	0	0	565	0	0	0	0	0	236	0	0	1324	494	0	0	0	0
4	110	0	0	0	1697	1151	0	0	0	0	0	1251	0	0	0	444	0	0	0	8
5	0	0	0	0	0	0	183	979	0	0	0	0	1710	0	0	599	0	0	0	0
6	0	0	298	0	0	0	0	836	0	0	0	0	352	0	0	317	0	0	0	0
7	0	0	0	0	0	0	0	0	0	1977	998	0	275	0	0	0	0	0	0	1034
8	2382	0	0	0	0	0	0	0	0	1539	896	91	0	0	0	0	0	0	0	761
9	0	0	0	0	0	908	0	0	0	321	730	0	0	0	0	0	0	0	0	565
10	0	0	0	0	2016	0	0	1166	0	0	0	0	644	0	0	0	0	0	0	504

8.3.2. Conditional Value at Risk (CVaR)

8.3.2.1. Data

In this model also the Capacity and availability of shelters are considered the same as two-stage stochastic model 2.

8.3.2.2. Result

α =0.8

The objective value is 574,468.

Table 34: Optimal shelter locations before earthquake (α =0.8)

Shelters				
1	**2**	**3**	**4**	**5**
X				X

Table 35: Optimal shelter locations after earthquake (α =0.8)

Scenarios	Shelters 1	2	3	4	5
1		X	X	X	
2		X	X	X	
3		X	X	X	
4		X	X		
5		X	X		
6		X	X		
7		X	X	X	
8		X	X	X	
9		X	X	X	
10		X	X		
11		X			
12		X	X		
13		X			
14		X			
15			X		
16					
17					
18					

Table 36: Transported people to shelters (α =0.8)

	Shelter location																								
	1	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
	1					**5**					**9**					**13**					**17**				
Demand zone 1	0	0	0	0	0	0	632	0	0	858	0	414	0	0	0	0	828	0	0	317	0	429	729	0	154
2	497	0	0	0	0	1174	0	0	0	0	2740	0	0	0	0	1052	0	382	246	0	0	0	0	0	0
3	0	0	298	0	0	0	0	0	0	0	0	0	1612	0	0	0	0	0	0	0	0	0	0	0	0
4	169	0	0	0	0	0	0	0	0	0	424	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	4126	0	0	0	0	0	487	0	0	0	1290	591	0	0	0	1424	637	692	0	0	569	182
6	0	1021	0	0	1471	0	0	0	0	1002	0	806	0	1404	0	0	255	0	1224	0	0	593	151	317	251
7	2273	0	0	0	0	1319	0	0	0	0	30	0	0	0	0	568	0	522	0	0	0	0	0	0	0
8	0	0	2086	0	0	0	0	298	0	0	0	0	639	0	730	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	2371	0	1268	0	1301	612	332	0	0	0	0	0	0	869	330	0	0	0	0

	2					6					10					14					18				
1	0	0	0	0	0	0	0	0	0	0	0	987	0	0	1131	0	0	0	0	0	0	0	855	637	38
2	199	0	0	0	0	0	0	0	0	0	1539	0	348	0	0	1007	121	581	0	0	0	0	0	0	0
3	0	0	0	712	0	0	0	0	0	0	0	0	850	1497	0	0	0	0	0	0	0	0	0	0	0
4	169	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	2063	0	2824	0	0	0	0	0	0	0	571	0	0	501	0	989	614	1135	780	0	0	327
6	0	2303	0	0	189	0	2492	0	0	0	0	0	0	506	0	0	0	0	0	0	596	0	176	0	322
7	2571	0	0	0	0	2383	10	0	0	100	883	0	0	0	0	643	0	418	0	0	0	0	0	0	0
8	0	0	1672	0	0	0	0	0	0	298	0	0	634	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	889	0	904	0	1016	1008	0	576	0	770	583	0	626	0	494	0

	3					7					11					15				
1	0	0	0	0	0	0	0	0	0	0	0	858	0	0	673	258	1078	0	0	0
2	107	0	0	0	0	1680	0	0	0	0	350	0	1458	0	0	0	0	0	0	0
3	0	0	1989	0	0	0	0	764	0	0	0	0	0	0	0	1324	0	806	0	0
4	169	0	0	0	0	424	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	2579	0	0	0	0	3340	0	1034	0	0	1138	0	0	0	0	645	296
6	0	2492	0	0	0	0	335	0	2289	0	0	0	0	592	501	0	709	0	579	0
7	2663	0	0	0	0	1090	0	0	0	0	660	0	302	0	0	0	0	0	0	0
8	0	0	395	0	0	0	0	1043	0	1174	0	0	0	0	0	0	0	486	0	365
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	1547	0	0	46	176	0	0	564	0	1186	0	42	0	666	0	0	123	0

	4					8					12					16				
1	0	0	0	0	0	0	565	0	0	1229	0	0	0	998	639	770	494	599	0	0
2	728	0	0	0	0	1590	0	0	0	0	0	1560	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	1162	0	0	0	0	1710	275	0	0	0	0	0	0
4	0	0	0	0	0	424	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	1977	0	2271	0	0	0	91	0	0	0	1034	565
6	0	0	0	2492	0	0	647	0	0	183	0	0	0	987	0	0	444	317	0	0
7	1765	0	0	0	0	1180	0	0	0	0	1192	18	0	0	0	0	0	0	0	0
8	0	0	298	0	0	0	0	836	0	983	0	0	352	0	644	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	1697	0	0	2016	106	504	0	1539	0	0	1233	0	0	0	441	8	0	761	504

α =0.9

The objective values is 899,439.

Table 37: Optimal shelter locations before earthquake (α =0.9)

Shelters				
1	**2**	**3**	**4**	**5**
X				X

Table 38: Optimal shelter locations after earthquake (α =0.9)

		Shelters				
		1	**2**	**3**	**4**	**5**
Scenarios	**1**		X	X	X	
	2		X	X	X	
	3		X	X	X	
	4		X	X		
	5		X	X		
	6		X	X		
	7		X	X	X	
	8		X	X	X	
	9		X	X	X	
	10		X	X		
	11		X			
	12		X	X		
	13		X			
	14		X			
	15			X		
	16					
	17					
	18					

Table 39: Number of population left at demand zones under each scenario (α=0.9)

		Scenarios																	
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Number of population left at demand zones	**1**	3,543	3,660	6,051	2,350	1,595	1717	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3	3,313	2,488	4,311	1,974	1,084	3,119	1,656	679	1,741	0	0	0	0	0	0	0	0	0
	4	0	0	1803	110	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	1,231	2,325	1,235	2,395	2,917	3,419	0	0	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	969	307	704	0	0	0	0	0	0	0	0	0	0	0	0
	7	2,555	1,180	0	4,137	2,277	2,546	0	0	0	0	0	0	0	0	0	0	0	0
	8	3,424	3,078	2,809	553	0	1,975	158	0	0	0	0	0	0	0	0	0	0	0
	9	3,815	2,457	1,182	2,261	0	1,461	1,908	0	0	0	0	0	0	0	0	0	0	0
	10	3,476	2,143	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	**21,357**	**17,331**	**17,391**	**14,749**	**8,180**	**14,941**	**3,722**	**679**	**1,741**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 40: Transported people to shelters (α=0.9)

Demand zone	Shelter location																								
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	1					**5**					**9**					**13**					**17**				
1	0	497	0	169	0	0	1174	0	0	0	0	2740	0	424	0	0	1052	0	0	0	0	0	0	0	692
2	0	2273	0	0	0	0	1319	0	0	0	0	30	0	0	1301	0	568	0	0	0	0	0	0	0	330
3	0	0	0	0	0	632	0	0	0	0	414	0	0	0	0	828	0	0	0	0	429	0	0	0	0
4	1021	0	0	0	0	0	0	0	0	2371	1418	0	0	0	0	255	0	0	0	0	593	0	0	0	0
5	0	0	298	0	0	0	0	0	0	0	0	0	1612	0	0	0	382	0	0	0	729	0	0	0	0
6	0	0	2086	0	0	0	0	298	0	0	0	0	639	0	332	0	522	0	0	0	151	0	0	0	0
7	0	0	0	0	4126	0	0	0	0	0	0	0	0	0	1290	0	246	0	0	1424	0	0	0	0	569
8	1471	0	0	0	0	0	0	0	0	1268	201	0	0	0	1203	587	0	0	0	637	317	0	0	0	0
9	0	0	0	0	0	858	0	0	0	487	591	0	0	0	0	954	0	0	0	0	154	0	0	0	182
10	0	0	0	0	0	1002	0	0	0	0	0	0	730	0	0	0	0	0	0	869	251	0	0	0	0
	2					**6**					**10**					**14**					**18**				
1	0	199	0	169	0	0	0	0	0	2824	0	1539	0	0	0	0	1007	0	0	0	0	0	0	0	1135
2	0	2571	0	0	0	0	2383	0	0	0	0	883	0	0	0	0	643	0	0	0	596	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	987	0	0	0	0	0	539	0	0	83	0	0	0	0	780
4	2303	0	0	0	0	2492	10	0	0	0	904	0	0	0	0	0	0	0	0	576	38	0	0	0	588
5	0	0	0	0	0	0	0	0	0	0	0	348	850	0	0	0	581	0	0	0	855	0	0	0	0
6	0	0	1672	0	0	0	0	0	0	0	0	0	634	0	0	0	0	0	0	418	176	0	0	0	0
7	0	0	712	0	2063	0	0	0	0	0	0	0	1497	0	571	0	0	0	0	989	637	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1522	0	0	0	0	770	0	0	0	0	494
9	0	0	0	0	0	0	0	0	0	0	733	0	0	0	398	0	0	0	0	614	0	0	0	0	365
10	189	0	0	0	0	0	100	298	0	889	0	0	0	0	1008	0	0	0	0	583	322	0	0	0	0
	3					**7**					**11**					**15**									
1	0	107	0	169	0	0	1680	0	424	0	0	652	0	0	732	258	0	1324	0	0					
2	0	2663	0	0	0	0	1090	0	0	46	0	660	0	0	0	0	0	0	0	666					
3	0	0	0	0	0	0	0	0	0	0	858	0	0	0	0	1078	0	0	0	0					
4	0	0	0	0	0	335	0	0	0	176	0	0	0	0	1186	709	0	0	0	0					
5	0	0	1989	0	0	0	0	764	0	0	0	1458	0	0	0	0	0	806	0	0					
6	0	0	395	0	1547	0	0	1043	0	0	302	0	0	0	0	0	0	486	0	0					
7	0	0	0	0	2579	0	0	0	0	3340	0	0	0	0	1138	0	0	0	0	645					
8	1033	0	0	0	0	2289	0	0	0	0	634	0	0	0	0	579	0	0	0	123					
9	0	0	0	0	0	0	0	0	0	0	329	0	0	0	344	0	0	0	0	296					
10	1459	0	0	0	0	0	0	1174	0	564	501	0	0	0	0	0	0	365	0	0					
	4					**8**					**12**					**16**									

	1	0	728	0	0	0	0	1590	0	424	0	0	0	0	0	2271	770	0	0	0	0
	2	0	1765	0	0	0	0	1180	0	0	106	0	1192	0	0	0	0	0	0	0	441
	3	0	0	0	0	0	565	0	0	0	0	0	966	0	0	594	494	0	0	0	0
	4	110	0	0	0	1697	0	0	0	0	1151	1251	0	0	0	0	444	0	0	0	8
	5	0	0	0	0	0	0	0	1162	0	0	0	0	1710	0	0	599	0	0	0	0
	6	0	0	298	0	0	0	0	836	0	0	0	0	352	0	0	317	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	1977	998	0	275	0	0	0	0	0	0	1034
	8	2382	0	0	0	0	1539	0	0	0	0	375	612	0	0	0	0	0	0	0	761
	9	0	0	0	0	0	337	0	0	0	892	0	0	0	0	730	0	0	0	0	565
	10	0	0	0	0	2016	183	0	983	0	0	0	0	644	0	0	0	0	0	0	504

α =0.95

The objective values is 1,007,121.

Table 41: Optimal shelter locations before earthquake (α =0.95)

Shelters				
1	**2**	**3**	**4**	**5**
X				X

Table 42: Optimal shelter locations after earthquake (α =0.95)

		Shelters				
		1	**2**	**3**	**4**	**5**
Scenarios	**1**		X	X	X	
	2		X	X	X	
	3		X	X	X	
	4		X	X		
	5		X	X		
	6		X	X		
	7		X	X	X	
	8		X	X	X	
	9		X	X	X	
	10		X	X		
	11		X			
	12		X	X		
	13		X			

	14		X			
	15			X		
	16					
	17					
	18					

Table 43: Number of population left at demand zones under each scenario (α=0.95)

Number of population left at each demand zone	Scenarios																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	3543	3660	6051	2350	1595	1717	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	3313	2488	4311	1974	1084	3119	1656	679	1741	0	0	0	0	0	0	0	0	0
4	0	0	344	110	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	1231	2325	1235	2395	2917	3419	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	969	307	704	0	0	0	0	0	0	0	0	0	0	0	0
7	2555	1180	0	4137	2277	2546	0	0	0	0	0	0	0	0	0	0	0	0
8	3424	3078	2809	553	0	1975	158	0	0	0	0	0	0	0	0	0	0	0
9	3815	2457	1182	2261	0	1461	1908	0	0	0	0	0	0	0	0	0	0	0
10	3476	2143	1459	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	**21357**	**17331**	**17391**	**14749**	**8180**	**14941**	**3722**	**679**	**1741**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 44: Transported people to shelters (α=0.95)

		Shelter location																								
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
		1					5					9					13					17				
Demand zones	1	0	497	0	169	0	0	1174	0	0	0	0	2740	0	424	0	0	1052	0	0	0	0	0	0	0	692
	2	0	2273	0	0	0	0	1319	0	0	0	0	30	0	0	1301	0	568	0	0	0	0	0	0	0	330
	3	0	0	0	0	0	632	0	0	0	0	414	0	0	0	0	828	0	0	0	0	429	0	0	0	0
	4	1021	0	0	0	0	0	0	0	0	2371	1418	0	0	0	0	0	0	0	0	255	593	0	0	0	0
	5	0	0	298	0	0	0	0	0	0	0	0	0	1612	0	0	0	382	0	0	0	729	0	0	0	0
	6	0	0	2086	0	0	0	0	298	0	0	0	0	639	0	332	0	522	0	0	0	151	0	0	0	0
	7	0	0	0	0	4126	0	0	0	0	0	0	0	0	0	1290	0	246	0	0	1424	0	0	0	0	569
	8	1471	0	0	0	0	0	0	0	0	1268	201	0	0	0	1203	1224	0	0	0	0	317	0	0	0	0
	9	0	0	0	0	0	858	0	0	0	487	591	0	0	0	0	572	0	0	0	382	154	0	0	0	182
	10	0	0	0	0	0	1002	0	0	0	0	0	0	730	0	0	0	0	0	0	869	251	0	0	0	0
		2					6					10					14					18				
	1	0	199	0	169	0	0	0	0	0	2824	0	1539	0	0	0	0	1007	0	0	0	0	0	0	0	1135
	2	0	2571	0	0	0	0	2383	0	0	0	0	883	0	0	0	0	643	0	0	0	596	0	0	0	0
	3	0	0	0	0	0	0	0	0	0	0	987	0	0	0	0	0	539	0	0	83	0	0	0	0	780
	4	2303	0	0	0	0	2492	10	0	0	0	904	0	0	0	0	0	0	0	0	576	360	0	0	0	266
	5	0	0	0	0	0	0	0	0	0	0	0	348	850	0	0	0	581	0	0	0	855	0	0	0	0
	6	0	0	1672	0	0	0	0	0	0	0	0	0	634	0	0	0	0	0	0	418	176	0	0	0	0
	7	0	0	712	0	2063	0	0	0	0	0	0	0	1497	0	571	0	0	0	0	989	637	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0	733	0	0	0	789	0	0	0	0	770	0	0	0	0	494
	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1131	0	0	0	0	614	0	0	0	0	365
	10	189	0	0	0	0	0	100	298	0	889	0	0	0	0	1008	0	0	0	0	583	0	0	0	0	322
		3					7					11					15									
	1	0	107	0	169	0	0	1680	0	424	0	0	429	0	0	955	258	0	1324	0	0					
	2	0	2663	0	0	0	0	1090	0	0	46	0	660	0	0	0	0	0	0	0	666					
	3	0	0	0	0	0	0	0	0	0	0	858	0	0	0	0	1078	0	0	0	0					
	4	2492	0	0	0	0	335	0	0	0	176	1186	0	0	0	0	709	0	0	0	0					
	5	0	0	1989	0	0	0	0	764	0	0	0	1458	0	0	0	0	0	806	0	0					
	6	0	0	395	0	1547	0	0	1043	0	0	79	223	0	0	0	0	0	486	0	0					
	7	0	0	0	0	2579	0	0	0	0	3340	0	0	0	0	1138	0	0	0	0	645					
	8	0	0	0	0	0	2289	0	0	0	0	0	0	0	0	634	579	0	0	0	123					
	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	673	0	0	0	0	296					
	10	0	0	0	0	0	0	0	1174	0	564	501	0	0	0	0	0	0	365	0	0					
		4					8					12					16									

	1	0	728	0	0	0	0	1590	0	424	0	0	0	0	0	2271	770	0	0	0	0
	2	0	1765	0	0	0	0	997	0	0	289	0	1192	0	0	0	0	0	0	0	441
	3	0	0	0	0	0	565	0	0	0	0	0	1487	0	0	73	494	0	0	0	0
	4	0	0	0	0	1697	0	0	0	0	1151	0	0	0	0	1251	444	0	0	0	8
	5	0	0	0	0	0	0	183	979	0	0	0	0	1710	0	0	599	0	0	0	0
	6	0	0	298	0	0	0	0	836	0	0	0	0	352	0	0	317	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	1977	998	0	275	0	0	0	0	0	0	1034
	8	2492	0	0	0	0	830	0	0	0	709	987	0	0	0	0	0	0	0	0	761
	9	0	0	0	0	0	1229	0	0	0	0	639	91	0	0	0	0	0	0	0	565
	10	0	0	0	0	2016	0	0	1166	0	0	0	0	644	0	0	0	0	0	0	504